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Kerstin Nordström

Gully erosion in the Lesotho lowlands

A geomorphological study of the interactions between intrinsic and extrinsic variables

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Gully erosion in the Lesotho lowlands - a geomorphological study of the interactions between intrinsic and extrinsic variables

Kerstin Nordström

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ABSTRACT

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The catchments were selected in pairs with similar climatic conditions. Aerial photographs from 1950, 1961/62 and 1979/80 were used to map the extent and development of gully erosion. Drainage density and gully area were measured in the air photos and the erosion rate calculated. Several other parameters were determined by air photo interpretation and in the field, e.g. soils, extent of piping and sheet erosion, and slope. To obtain a database for statistical analyses the catchments were divided into grids (200 x 200 m) and the parameters defined for each square.

Annual and monthly rainfall records since 1921 were analysed and 10-year averages and rainfall trends calculated. An analysis of the monthly records reveals that several potentially erosive dry-wet sequels occurred during the period under study (1950-1980). A meteorological station in the northern lowlands displays steeply declining annual rainfall.

The catchments are ranked according to how severely eroded they are and it is shown that the cycles of gully erosion in the Lesotho lowlands are truly highly local. Areas within the same region may show entirely different erosion rates and gully extent. The effects of different intrinsic and extrinsic variables on gully erosion in Lesotho are analysed. The complexity of the problem is discussed and it is concluded that: it is the overall effect of several stress factors that causes the threshold of intense gully erosion to be transgressed. Furthermore, the differences in erosion cannot be ascribed to rainfall alone; gully erosion and piping are not isolated to duplex soils; slope angle does not have a direct impact on gully erosion, gullies may develop on very low slopes; where depth of erodible material to bedrock is limited, gully widening is a prominent process; the effects of a change in baselevel are highly local in character but may be morphologically significant; tree planting along the gullies to limit further development has not been successful, in fact, quite the opposite in areas with piping-prone soils; unsuitable cultivation methods and conservation measures have contributed greatly to gully erosion, and the effects of installing terraces and grass strips have not been entirely positive. A certain amount of gully erosion is natural but the human activities have not been in harmony with the environment. The impact of extrinsic variables (e.g. landuse) in accelerating the process of gully erosion has been considerable.

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Keywords: Lesotho lowlands, gully erosion, cyclic gully erosion, soil erosion, accelerated erosion, rainfall variation, historical aspects

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Kerstin Nordström

GULLY EROSION IN THE LESOTHO LOWLANDS - A GEOMORPHOLOGICAL STUDY OF THE INTERACTIONS BETWEEN INTRINSIC AND EXTRINSIC VARIABLES.

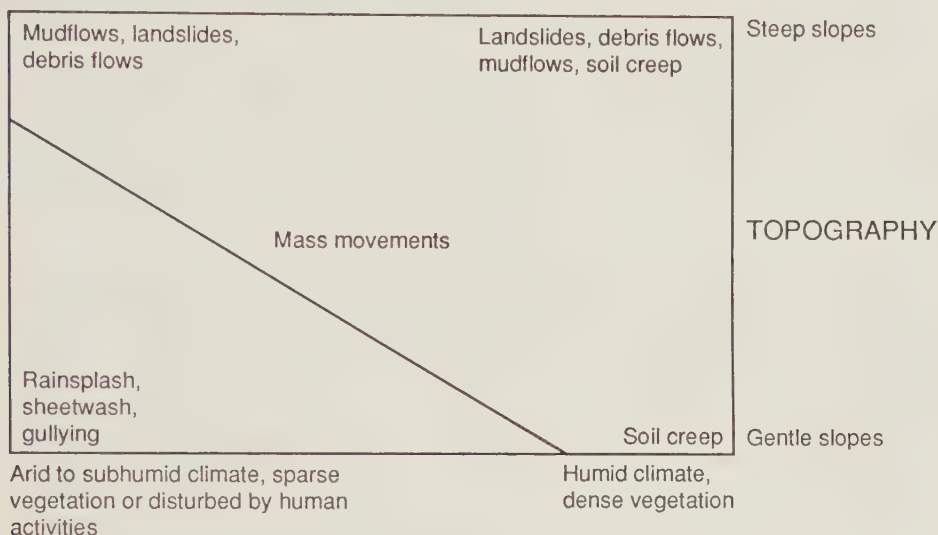
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1 INTRODUCTION

1.1 Gully erosion in subtropical environments - an introduction to the problem.

Soil erosion and mass movement are well known phenomena all over the world. The processes differ depending on environmental factors such as climate, topography, vegetation, soil and landuse. The influence of the latter may be more or less pronounced depending on the other four. Figure 1.1 gives an impression of how the processes in different regions vary depending on the environment. Gullying is extensive on relatively gentle slopes in arid to subhumid climates.



CLIMATE, VEGETATION AND LANDUSE

Figure 1.1. Conditions of climate, vegetation, landuse and topography during which different erosion processes dominate (after Dunne & Leopold, 1978).

Several definitions of gullies have been put forward. A summary of some of these (Moss & Walker, 1978; Bradford & Piess, 1978; Imeson & Kwaad, 1980), and some personal observations would suggest the following characteristics of a gully:

- a steep incised channel, often with a sharp headcut.
- not permanently occupied by flowing water.
- has shown or is showing rapid growth and/or extension.
- mostly limited to unconsolidated slope deposits and deeply weathered soils but may sometimes develop in erodible bedrock.

Although gullies may sometimes be regarded as spectacular elements of the landscape, the process of gully erosion is purely destructive. Sheet erosion is generally more laterally spread out than gully erosion and may therefore be more harmful to, for example, agricultural land in removing the topsoil, but gully erosion has other severe consequences. Large volumes of soil are lost at depth as the gully erodes its way through the soil profile. Gullies, while extending (increase in length) and expanding (increase in width), encroach upon fields, roads and villages. The eroded soil is washed away and may be deposited further downstream, accelerating the silting of reservoirs. The water quality downstream is impaired through an increase in suspended and dissolved load, and by a lowering of the pH (Schouten & Rang, 1984). Less directly, by draining the adjacent fields and lowering the water table,

gullying will reduce crop yields (Jepson, 1939; Tejwanj, 1975). Since reduced crop yields imply less ground cover and hence more erosion, we have entered a vicious spiral, heading downwards.

The severity of gully erosion in a catchment is sometimes quantified as a percentage of the total area. This figure may seem insignificant in some cases but it should be noted that this is just a measure of the land area lost directly through gullying. The gullies dissect the fields into small and irregular units and thereby preclude an efficient landuse. The land closest to the gully cannot be used due to erosion risks. The area affected in reality is therefore much larger than the area covered by the gully itself.

The factors affecting gully erosion can be divided into intrinsic variables that exist within the geomorphological system, e.g. soils, vegetation, morphology and climate, and extrinsic variables (e.g. overgrazing and farming practices) that are foreign to the system and cause the system variables to change (Stocking, 1981).

Numerous papers have been written on gully erosion. Several authors have concentrated on the processes directly responsible for the initiation and growth of gullies (e.g. Veness, 1980), others have approached the problem through theories of equilibrium and stability (e.g. Graf, 1979). However, the relations between rapid gully erosion and extrinsic/intrinsic variables are still not fully understood. Research has indicated that periods of stagnation are followed by periods of rapid expansion and extension (e.g. Ireland et al., 1939). Gully systems develop in conjunction with concentrated drainage caused by roads, paths and conservation measures, and in connection with heavy rainfall etc.

Is, in fact, some kind of threshold involved that has to be crossed before erosion increases, as suggested for example by Patton and Schumm (1975)? There is, perhaps, a connection with vegetation cover, rainfall intensity etc. What determines when a specific threshold is reached? What are the triggering mechanisms? How important are different intrinsic and extrinsic variables? Is gully erosion just a natural process accelerated by human impact as suggested for example by Moss and Walker (1978), Stocking (1981), and Dregne (1983)?

The problem is very complex and no simple answer can probably be found. The different variables influence and interact with each other according to an intricate pattern. Figure 1.2 is a hypothetical model and an attempt to summarize and tie together the factors that affect gully erosion.

Gully erosion in Lesotho has previously been studied by, for example, Chakela (1974; 1981), Rooyani (1981), Faber and Imeson (1982), Strömquist et al. (1985), Nordström (1986 a, b), and Lundén et al. (1986), all of whom mainly dealt with the processes leading to the development of gullies, and Flannery (1976) who discussed gully reclamation and control.

1.2 Aim of study

This study attempts to find some explanations to the problem of gully erosion in general, and in Lesotho in particular. The aim of the study is to:

1. Determine the present state of gully erosion in selected areas in Lesotho, and identify the ones most severely eroded.
2. Determine the effects on gully erosion in Lesotho of the factors discussed in Section 2, i.e. the morphology of the drainage basin, climate, soils and geology, baselevel, vegetation, and human impact.
3. Analyse and explain the differences in gully extent and erosion rates between the different areas.

The study is an analysis of the process of gully erosion and related variables and only deals speculatively with possible conservation methods or protective measures specifically aimed at preventing gully initiation and development.

Section 2 of this study is a summary of the different variables and concepts connected with gully erosion. It is theoretical, but with a systematic approach aimed at providing the scientific background to the case study. Section 3 is a practical part, giving the geographical background of Lesotho and describing the study areas and methods used. Section 4 contains the results of the study which then are discussed in Section 5. The results are summarized in Section 6.

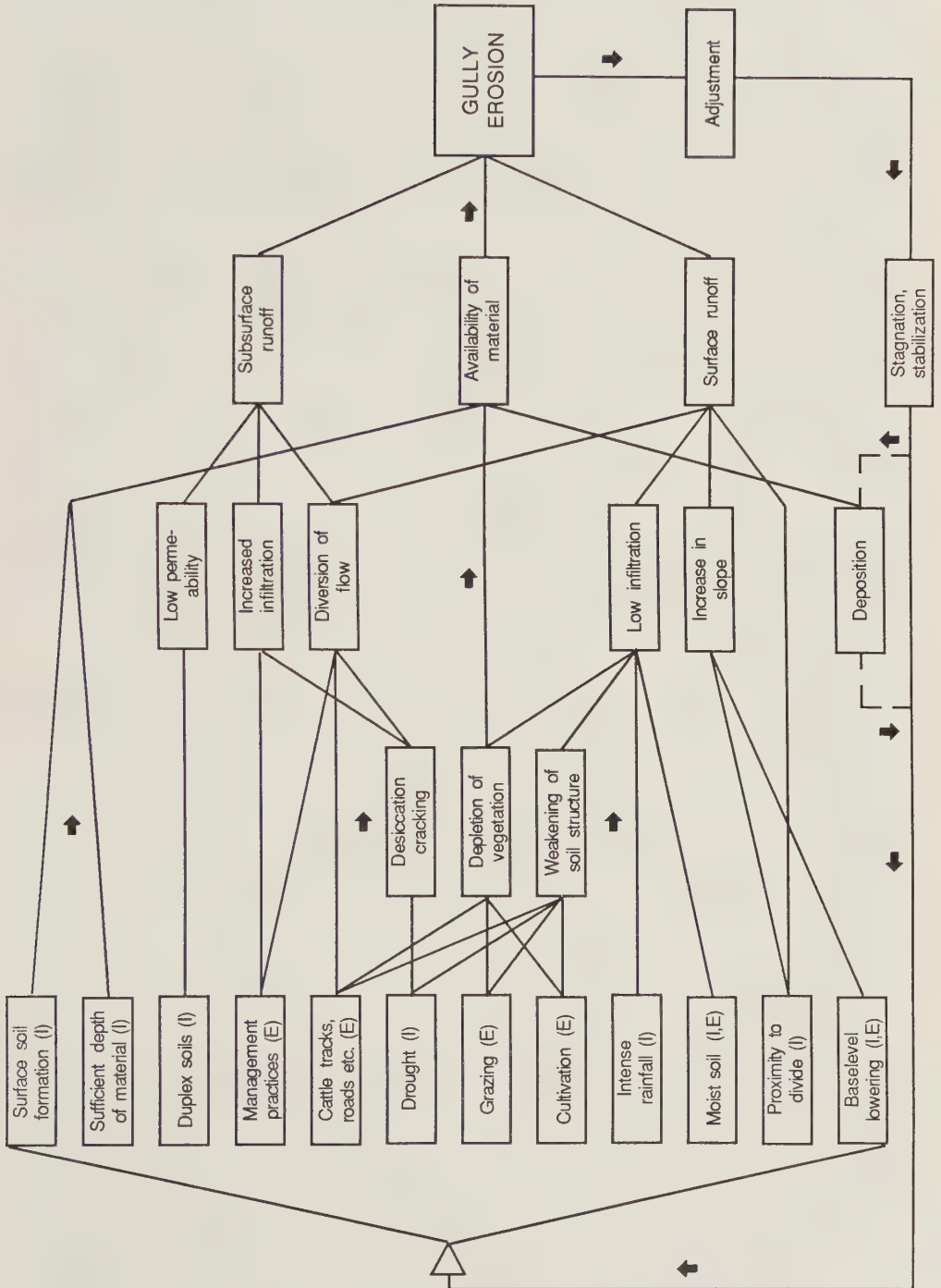


Figure 1.2. Schematic figure of the cycle of gully erosion. Two prerequisites for gullying to occur are: and eroding agent (surface or subsurface runoff), and erodible material. These prerequisites are affected by a number of intrinsic (I) and extrinsic (E) variables that in a complicated pattern interact and may push the system over a threshold, initiating a new cycle of gully erosion.

2 SCIENTIFIC BACKGROUND

2.1 Soil erosion In general and runoff generation

The rate of soil erosion caused by flowing water is controlled by two fundamental variables: the erosivity of the flow, and the erodibility of the material (Graf, 1979). The resistance (shear strength) of an unconsolidated material to applied shear stress depends on friction and cohesion. As soon as the shear stress exceeds the shear strength, the flow becomes erosive. The stress exerted by the flow is largely dependent on its velocity, which in turn depends on roughness, depth of flow, and slope (Manning and Chezy formulas). The velocity decreases with increased roughness and sediment load, and decreased depth of flow and slope. An increase in the sediment load of the flow will increase the viscosity and thereby reduce the velocity and erosivity (Sundborg, 1956). The capacity of the flowing water to carry sediment and erode is thus affected by the factors mentioned. If the sediment load is at the maximum capacity the erosivity is low and vice versa. Múcher and De Ploey (1977) found that on a slope of 0.5°, sedimentation of loess loam started, even during heavy showers (90 mm/h), when sediment concentration exceeded 125 g/l. Hence, with a sediment load that high, the runoff was no longer erosive.

The erodibility of the sediment can be expressed as a relationship between particle size and flow velocity (Hjulström, 1935). For noncoherent materials of uniform specific gravity the threshold of entrainment is at its lowest for particle sizes between 0.1 and 0.5 mm, it then increases for larger and smaller particles respectively. Dry soil particles are more easily eroded than cohesive and wet ones (Wilson, 1973).

Soils with large pores have high infiltration capacity, which is favoured by large grains, sorting, root penetration, and aggregation by organic matter or small amounts of clay. A sandy soil has a high infiltration capacity due to the large grains. A clayey soil is subjected to cracking through wetting and drying. This increases infiltration to some extent but as soil moisture increases the clay will swell, the cracks close and infiltration is reduced to nil. Hence, a wet clayey soil generates runoff more quickly during a rain than a dry soil.

The flow volume over a soil surface is basically determined by the amount of rainfall, the infiltration capacity and the surface detention capacity (Dunne & Leopold, 1978). Infiltration capacity can be defined as: "a maximum rate at which the soil in a given condition can absorb water" (*ibid.*). The factors influencing the infiltration capacity are listed in Table 1. The rate of infiltration declines rapidly during a storm and drops to a relatively constant level within one to two hours (*ibid.*).

A less permeable sublayer in the soil profile may cause the pore spaces in the top horizon to fill up, thus reducing infiltration. The pore-water pressure builds up in the surface horizon making it more erodible (Harmse, 1974). The microtopography of the soil surface influences the velocity of the runoff, e.g. a rough surface slows it down. Small depressions in the soil surface also increase the detention of water on the surface, thereby increasing the time water is available for infiltration.

Vegetation is generally considered to protect the soil surface from erosion, but this is not always the case. Root penetration increases the porosity of the soil and thus infiltration. A dense vegetation and litter cover increases the surface roughness, which reduces the erosivity of the runoff. This also increases the detention of water on the soil surface, giving it more time to infiltrate.

Vegetation reduces the impact of raindrops (splash erosion) by intercepting the rain (Ellison, 1944). This is, however, only true for near ground cover. On broad-leaved trees the drops coalesce on the leaves forming larger drops that overcome surface detention, and drop off (e.g. Dunne & Leopold, 1978; Meyer, 1981). The energy of these drops (the through-fall) can actually be greater than that of the rain itself. This was noted by Mosley (1982) who recorded that splash erosion under a beech forest canopy in New Zealand was about 3 times greater than in the open. He further noted that this would in fact mean that a long-lasting, originally non-erosive, rain could become highly erosive by falling on a tall canopy cover.

The type of trees is also important. Eucalyptus species, for example, produce very sparse and friable litter, while the litter from pines is dense and has a high water retention capacity (Powell & Wellings, 1983). In addition to reducing runoff, the litter cover protects the surface from rain splash. Kulander (1986) found that the litter cover under a pine tree plantation in Lesotho amounted to 95 % while the equivalent figure for a eucalyptus plantation was only 10 %.

On a long-term basis climate exerts great influence on, for example, soil formation. On a shorter time scale the most important factors, temperature and precipitation, have more immediate effects on infiltration and runoff. Temperature affects the evaporation rate and thus, to some extent, the amount of runoff. It also influences the type of vegetation and transpiration rate, and the amount of swelling and cracking on clayey soils.

A high annual rainfall of an unfavourable character, or if it falls in an area that cannot absorb it, is of little use as it leaves the soil as runoff. On the other hand, an area that receives the same amount of rain, evenly distributed over the year, may be able to support a protective vegetation cover. Areas that receive precipitation in the form of snow may experience saturation of the top soil during snow melt, which can lead to runoff and erosion.

Table 1. Factors affecting infiltration capacity. For comments, see the text (summarized from: Jepson, 1939; Zingg, 1940; Horton, 1945; Musgrave & Holtan, 1964; Chow, 1964; Dunne & Leopold, 1978; Strahler, 1975).

1. Soil factors:	- depth of soil profile - soil structure - pore size - grain size - clay content - compaction - permeability - soil moisture - organic matter content
2. Vegetation factors:	- root penetration - interception - density - transpiration - type and composition
3. Climatic factors:	- rain intensity - frequency of rainfall events - duration of rainfall - type of precipitation - temperature
4. Water characteristics:	- sediment concentration - salt content - temperature
5. Basin characteristics:	- slope

Low intensity rains do not possess the energy to break up the soil aggregates. Hudson (1981), after experiments in Africa, concluded that an intensity of 25 mm/h could be used as a threshold value above which rainfall becomes erosive. This is the erosive power of the rain itself. Intense rains thereby break down the crumb structure of the soil, making the soil particles readily available for erosion through runoff. The finer particles may cause clogging of pores, and thereby reduced infiltration. Intense rains also saturate the top soil more quickly than less intense rains, creating runoff. However, depending on the top soil conditions, rains of lower intensity may also be erosive, by causing runoff. Rydgren (1986), studying the effects of landuse on runoff in Lesotho, found that an intensity of 15 mm/h was needed to create surface runoff on cultivated lands. On grazing land, on the other hand, an intensity of 3-5 mm/h was sufficient to create runoff, presumably due to trampling and compaction of the top soil.

Frequent rains keep the soil moist which is favourable for the vegetation and for the soil structure. This has a positive effect and decreases the runoff and erosion. However, wet soils

produce more runoff than dry soils. The detachability of soil particles on a bare soil increases with increasing soil moisture (Wolman & Miller, 1960). Luk & Hamilton (1986), working on two loamy soils in Canada, noted a difference as great as 800 times if the full range of soil moisture was considered, i.e. the soil loss increased with antecedent moisture content. As mentioned above, a high moisture content of clayey soils will keep the cracks closed, decrease the infiltration and accentuate the problem.

The factors of antecedent precipitation and timing are also important. In seasonal climates, for example, the ground is highly vulnerable to erosion at the beginning of the rainy season, when the vegetation cover is sparse. A series of dry years followed by a wet year will have a similar effect. The drought results in depletion of vegetation which in turn leads to weakening of the soil structure and increased erodibility. Therefore a series of dry years followed by a wet year may cause severe erosion in areas where a sequence of "normal" years hardly would cause any damage at all. This has been suggested in connection with gully erosion for example by Cooke and Reeves (1976) and Strömquist et al. (1985). The effect is similar if rainfall variability is high. A month, or series of months with below normal rainfall will reduce vegetation cover and a following rainy period will have severe effects on erosion. In a seasonally wet climate, high variability during the dry season, when the vegetation cover is sparse, may result in heavy rainfall when the soil is least protected, resulting in erosion.

A severe storm that causes erosion may remove most of the available loose material. A following heavy downpour will then cause less erosion since no material is available (Snyman & van Rensburg, 1986). However, as intense storms are generally very local, the impact of the latter storm may simply be moved with the runoff to an area further down in the drainage basin. The velocity of the runoff will be high and the sediment load very low, making it highly erosive.

Runoff and erosion both increase with slope. The infiltration capacity, however, may well be higher on the steeper slopes as the fines have been washed down and deposited on the flatter parts (Valentin & Roose, 1981; Poesen, 1984). The water rarely remains and infiltrates though due to the slope angle, especially during heavy showers, and on steep slopes therefore runoff is generated more quickly than on gentle slopes. The lack of water on steep slopes, due to runoff, also has a negative effect on plant production (Snyman & van Rensburg, 1986). Since the fines have been washed downslope, the availability of nutrients is low.

The salt content and the temperature of infiltrating water affect the viscosity (high viscosity reduces infiltration) and the former also affects the degree of chemical dispersion of the soil aggregates (see Section 2.2.2). The water that does infiltrate can either be transmitted as subsurface throughflow downslope through the unsaturated topsoil layer, or percolate through the whole soil profile down to the ground water table. In the former case the water may again reach the soil surface at some point further downslope, adding to the overland flow. In the latter case it may reach open air at a spring or well.

If precipitation during a storm exceeds the infiltration capacity, water will accumulate on the soil surface and fill small depressions. When the storage capacity is exhausted, runoff is initiated as a sheet of overland flow. The sheet increases in depth and velocity downslope along with its erosivity. At a critical distance from the hilltop shear stress exceeds shear strength and erosion can start (Horton, 1945). The distance is influenced by roughness, slope, resistance or erodibility of material, and the amount of flow. Variations in microtopography of the soil surface will cause concentration of flow at certain points. As a result of the greater depth of flow, erosion will be most rapid at these points and a network of rills can develop. The size and spacing of the rills vary with slope, runoff intensity, length of overland flow, and erodibility of soils. The rills may become enlarged and incised into the land surface and eventually turn into gullies. Further downslope, on more level ground, the flow velocity and erosivity decrease, eventually leading to deposition (*ibid.*).

The rate of soil erosion in a catchment is frequently measured at the discharge point of the major river in tonnes/km². This figure is somewhat misleading, since a far greater volume of soil can be eroded and deposited within the catchment without being recorded at the gauging station (Dunne & Leopold, 1978; Blandford, 1981). There is a decrease in sediment yield per unit area as the size of the catchment increases, due to the fact that the maximum erosion occurs in the head areas and there is a larger area available to receive deposition in larger basins (Schumm, 1977).

2.2 Gully erosion

Basically two types of runoff are responsible for gully initiation and excavation: overland flow and subsurface flow. They may act separately or in conjunction. The proportions of the two vary depending on a number of factors that affect infiltration, which have been discussed in the preceding section. Assuming that we have either type of flow, or both, the rate of gully erosion is determined by a complex pattern of interacting variables (Fig. 1.2). The potential for gully erosion in an area is limited by the distribution and availability of suitable (erodible) material (Bradford et al., 1978; Imeson & Kwaad, 1980).

2.2.1 Caused by surface runoff

Surface runoff is mainly responsible for the following gully erosion processes:

1. Gully initiation and deepening by downward scouring.
2. Undercutting of the gully walls by water flowing along the bottom of the gully.
3. Headward advance due to waterfall erosion and plunging (Ireland et al., 1939).

Gullies are sometimes initiated by a sequence of sheetwash-rill erosion-gully, as stated by Horton (1945), where runoff builds up on a sloping surface on a slope creating rills and, further downslope, a gully. This is not always the case, however. Sheet eroded surfaces are frequently found in direct connection with gullies without any sign of rill erosion. In addition, gully heads are often found, for example, in the middle of cultivated fields with no apparent sheet erosion. The reasons for this are environmental and depend on the processes in action and will be discussed in more detail in Section 2.3. As an overfall develops at the gully head, waterfall erosion can be initiated.

Headward advance due to this process is influenced mainly by the height of the headcut and the amount of water collected at the headcut (Jepson, 1939; Stocking, 1981). The higher the headcut, the greater the energy transfer and the more effective the process. The amount of water collected decreases with decreasing drainage area. The further the head advances upslope, the shorter the distance to the divide and, therefore, the smaller the drainage area. Gully widening is to a large extent a response to the maximum discharge experienced in the gully and as the head progresses towards the drainage divide the widening process is slowed down (Blong, 1970).

It is important to stress the significance of the suspended sediment and bedload concentration of the flow. As noted by Moss and Walker (1978), a gully head may develop immediately downhill from a vegetated surface because the flow is not loaded with sediment and hence erosive. Similarly they noted that if an erosion pavement is present in the gully bottom the flow is very erosive and the debris easily removed. The gully walls are exposed and the process of undermining prominent. The result is a shallow, broad and flat-floored gully. On the other hand, if the flow is loaded with sediment when entering the gully, undercutting may be restricted and the scree material along the walls may be left relatively undisturbed. In this case headcutting may be a more important agent of erosion than sidewall erosion.

The gully will continue to cut down and extend headwards, unless external or internal factors change in some way leading to stagnation. Erosion will finally cease when the drainage area has been reduced so that runoff is no longer sufficient and capable of eroding. Downward scouring ceases when resistant bedrock or a local baselevel is reached (e.g. the level of a main gully or river). The widening of the gully may still continue.

The rate of downcutting in the gully bottom further downslope from the head, is dependent on slope, amount of flow, and sediment concentration. The sediment load of the water flowing over the headcut increases as it proceeds along the gully bottom, which reduces the erosivity. Opposing this fact is the increase in flow volume downslope, added from the walls. Infiltration into the gully bed will reduce the volume of water and, unless sediment is deposited, increase the sediment concentration. As the slope decreases and the gully widens downstream, flow velocity and erosivity decrease. The result of this process can be observed in the field as a fan of sediment deposited in the downstream reaches of the gully, or at the gully mouth. Eventually extreme peak flows may be capable of eroding the deposited sediment, or a whole new cycle of erosion may be initiated.



2.2.2 Caused by subsurface runoff

Subsurface movement of water can take place in two forms (Berry, 1970): as a sheet of water soaking through a porous medium, or as a linear flow along specific joints, pores or bedding directions, animal holes, plant roots etc. The linear flow can be referred to as piping or tunnelling. The flow may follow linearities already present in the soil (e.g. root holes and cracks) or it may be independent in which case the erosion is caused by a concentration of subsurface drainage lines which do not necessarily follow cracks or root holes. The two types of linear subsurface flow have been treated as separate processes by some authors (e.g. Bryan & Harvey, 1985), others have treated them as one (e.g. Baillie, 1975). The latter view is adapted in this thesis.

The requirements for subsurface movement of water to occur are: a hydraulic gradient, a medium through which water can flow, and sufficient supply of water. All forms of subsurface flow (diffuse flow or piping/tunnelling) can cause gullies to form. The diffuse flow requires a free face of some kind in order to cause undermining and slumping. Piping and tunnelling cause gullying by linear subsurface erosion, which eventually reaches the soil surface resulting in an open gully. The problem of piping and tunnelling is much more complex and important than diffuse seepage when it comes to gully erosion and needs to be examined further.

Numerous authors have discussed piping and tunnelling. The most thorough and extensive review of the literature published up to 1981 was made by Jones (1981), who surveyed terminology, distribution, causes, morphometry, evolution, and the role of piping as an agent of erosion. For further readings I therefore refer to Jones' monograph.

The factors favouring the process of piping/tunnelling can be summarized as follows (Gibbs, 1945; Downes, 1946; Fletcher et al., 1954; Parker, 1963; Heede, 1971; Jones, 1971; Crouch, 1976; Barendregt & Ongley, 1977; McIntyre, 1979; Stocking, 1976; Bryan & Yair, 1982; Rooyani, 1985; Baillie et al., 1986):

- high infiltration rates
- hydraulic gradient within a soil layer
- a steep free face
- soil subjected to cracking
- high intensity rainfall
- a relatively impermeable layer further down in the soil profile
- an erodible layer above the impermeable layer
- reduction or change in vegetation cover
- favourable proportions of cations in pore fluid and soil
- high percent of swelling clays
- biotic breakup of soil (rodents, roots etc.)

A significant permeability difference between soil horizons is needed for the build-up of a hydraulic gradient and the initiation of subsurface water flow (Baillie, 1975). Soils with a sharp textural boundary between an upper coarser horizon and a lower finer (clayey) horizon are known as "duplex soils" (Faber & Imeson, 1982). The textural difference is commonly noted to occur between the A- and B-horizons but the same sequence can be found, and give rise to piping, at several levels in the soil profile. Jones (1971) gives the example of an old soil where the B-horizon has been buried and migrated down the profile. A sharp boundary between the C-horizon and the bedrock surface will have the same effect, as the bedrock is often less permeable than the soil above. Duplex soils, having a marked textural change between the A- and B-horizons, are thus considered to be particularly vulnerable to gully erosion through piping and tunnelling. Gully erosion has been described in connection with duplex soils in Australia (Charman, 1969; Crouch, 1983), Lesotho (Chakela, 1974; Conserv. Div., 1979a; Faber & Imeson, 1982; Rooyani, 1985) and South Africa (Downing, 1968), among other areas.

The depth and severity of tunnelling and piping depend largely on the properties of the lower horizon (B) (Jones, 1981). Water percolating through the A-horizon causes eluviation of clay particles. When the water reaches the B-horizon the smaller pores will get clogged. The water may also activate sodium present in the soil and cause dispersion. The rate of dispersion depends on the relationship between the ionic content of the soil and the percolating water. In soils with a high clay content the dispersion is accomplished by cationic exchange on the surface of the clay micelles. This involves a replacement of bonding divalent

cations such as Ca^{++} and Mg^{++} , by monovalent ions of Na^+ , K^+ or bicarbonate in the percolating water, thereby increasing the repulsive forces of the micelles. The most effective ion in causing dispersion is sodium. The critical stage at which instability occurs in clays is a function of the soluble sodium percentage and the clay mineral species (*ibid.*). A low content of salts in the seepage water increases the susceptibility to dispersion by increasing the potential for cation exchange (Sherard et al., 1972).

The relationship between the content of Na^+ , Mg^{++} and Ca^{++} in the soil is commonly expressed as the Sodium Adsorption Ratio (SAR):

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{(\text{Mg}^{++} + \text{Ca}^{++})}{2}}}$$

A measure of the sodium available in the soil is the Exchangeable Sodium Percentage (ESP):

$$\text{ESP} = \frac{\text{Na}^+}{\text{Cation Exchange Capacity}}$$

All values given in meq/100 gr soil.

The higher the ESP and the SAR, the more sodium is available to cause dispersion, and the higher the erodibility of the soil. Considering this, it is easy to assume that the erodibility of the soil and the potential for piping are automatically low for soils with low ESP and SAR values. The problem is more complex than this and some other factors have to be taken into consideration, too.

United States Salinity Laboratory Staff (USSLS, 1954) stated that an ESP of at least 15 is needed for soils to be affected physically when reacting with water (i.e. to be dispersed). This has later been questioned for example by Stocking (1980a) who found piping in soils in Zimbabwe with an ESP of 4-68, and McIntyre (1979) who suggested that an ESP less than 15 can cause dispersion if the concentration of Mg^{++} is greater than that of Ca^{++} . Rooyani (1985) reached the same conclusion and proposed that the ratio $\text{Mg}^{++} + \text{Ca}^{++} / \text{Na}^+$ is more realistic as an erosion index, with the erodibility increasing with the index.

Dispersion and the amount of swelling and shrinking of the soil during wetting and drying depend on the type and content of clay in the soil. A high content of clay, especially montmorillonite, increases the potential for dispersion and volumetric change (Parker, 1963). Imeson (1986) noted that it is not the potential for volumetric change as such within the soil that is most important for pipe development. More important is the way in which the potential varies with depth.

The climate influences piping and tunnelling mainly through precipitation and temperature. The latter affects the degree of desiccation cracking. Rainfall characteristics influence the infiltration rate and thereby the amount of swelling and cracking. High intensity rains fill up the pore spaces in the top soil and cause runoff in cracks etc. Although piping has been recorded in humid climates (e.g. Jones, 1971) where rainfall is evenly distributed over the year, a marked seasonality in rainfall encourages cracking, especially in combination with high temperatures (Bryan & Yair, 1982). The requirement for subsurface water to be present is that infiltration is possible. The development of piping and tunnelling is favoured by uneven infiltration over the soil surface, i.e. small patches of high infiltration alternating with patches of low infiltration (Downes, 1946). This can be caused for example by a densely vegetated patch with high infiltration on an otherwise bare soil surface (Beckedahl, 1977), or through a bare, clayey soil patch subjected to cracking, which increases infiltration (e.g. Brown, 1962; Blakemore, 1978).

Pipes can be discontinuous. As long as there is sufficient hydraulic gradient there can be lateral diffuse seepage. When the seepage reaches a crack or roothole, the flow is

concentrated and a small tunnel/pipe develops. Hence, the flow may change from seepage to piping/tunnelling depending on the structure of the soil.

Along the subsurface drainage lines, the soil is easily dispersed and eroded. As the pipe increases in length, its erosive capacity will also increase as the area it drains becomes larger (Parker, 1963; Löffler, 1974). Once developed, the pipe continues to erode downwards through the soil profile by scouring, and upwards through seeping and trickling of the percolating water. Finally it reaches the soil surface and causes collapse and slumping of the overburden soil. This process is discontinuous along the pipe, and so a chain of sinkholes is formed. They will eventually fuse together to form a gully. This process was recorded already by Rubey (1928). The ultimate downward limit is the resistant bedrock or the level of the main gully bottom.

Jones (1971) made a distinction between pipes connected directly with a channel or gully network and disjunct pipes that reach the channel via sheets of overland flow. In the former case pipe outlets are found on the gully walls and headcuts.

The size and shape of the pipes are mainly controlled by the erodibility of the soil (Jones, 1971). Their diameter varies from centimeters (e.g. Bryan et al., 1978) to several meters (e.g. Beckedahl, 1977). Vegetation with a dense root mat may prevent the pipe roof from collapsing, keeping the pipe invisible for a longer period of time.

Piping may occur on a wide range of slopes. Downes (1946) claimed the minimum slope required for piping to be 4° , but slopes of a smaller angle do not seem to be a limiting factor. Berry (1970) noted the occurrence of piping on slopes of less than 1° in Sudan. Yair et al. (1980), on the other hand, recorded piping on slopes of 35° in the badlands of the Negev, Israel. Baillie (1975) recorded a sharp decrease in piping above 20° in Sarawak, Malaysia. He noted that the ratio between surface and subsurface runoff increased with slope and therefore the infiltrated water was not sufficient to initiate piping. However, he did not distinguish between piping and tunnelling. The latter can be initiated with less amount of water since the drainage line already has developed. Lynn and Eyles (1984), mapping the extent of piping and gully erosion in New Zealand, noted that piping frequency was highest on slopes between 21° and 25° , and insignificant on slopes less than 7° and steeper than 35° . Jones (1971, p. 608) ascribed the occurrence of piping on both steep slopes and flat areas to the fact that "... the controlling factor is hydraulic gradient and not physiographic gradient. Hence, to develop on low slopes, piping requires a gully wall or stream bank nearby, whereas on steep slopes, pipe outlets may be found on the surface of the same slope segment as the inlet."

2.3 Gully processes and types

Once a gully has been initiated the processes responsible for further head cutting and tributary gully formation are:

- tributary gully development due to desiccation cracking on the main gully walls, which are more exposed to wetting and drying than areas further away (Chakela, 1974). These cracks then collect and concentrate the surface runoff. In addition, the gully wall will give rise to a hydraulic gradient, making them vulnerable to pipe development.
- tributary gully formation and headward advance due to piping and tunnelling (e.g. Rubey, 1928; Downes, 1946; Berry, 1970; Chakela, 1974; Löffler, 1974; Crouch, 1983).
- headward advance due to plunging, overfall and back trickle of water underneath an upper resistant horizon (e.g. Ireland et al., 1939; Blong, 1970; Stocking, 1980b). This causes caving and undermining that lead to tension cracks and finally a break.
- headcutting and growth due to seepage of water in a lower horizon. The seepage removes the soil in the wall, leading to undermining and slumping (e.g. Jones, 1971; Higgins, 1984).

The processes responsible for sidewall retreat and general growth are:

- lateral and headward growth due to undermining of the sidewalls in the main gully (e.g. Chakela, 1974; Crosby et al., 1979; Pizzuto, 1984).
- gully widening through fluting (Veness, 1980). Vertically elongated grooves, tapering towards the top, caused by the action of sediment loaded water flows and dry sediment flows on the gully sides.

- collapse and failure of gully walls due to reduced soil cohesion caused by wetting (Bradford & Piest, 1977).
- vertical cracks at the surface decrease the cohesion and reduce the overall stability. Water infiltrating from the surface into the cracks increases the water pressure and results in failure of the walls (Bradford & Piest, 1977).
- sidewall retreat due to cracks caused by wetting and drying resulting in soil fall (more effective on walls facing the sun due to more intense shrinkage effects) (De Ploey, 1974).
- freezing and thawing loosening the soil, which sloughs off and is carried away during heavy rains (more effective on walls facing the sun) (Jepson, 1939; Blong, 1966).
- wind erosion (Blong et al., 1982). Probably of minor importance.
- rainsplash on the gully walls and the surface above. Soil aggregates are destroyed and particles removed (e.g. Blong et al., 1982).
- gully widening due to sheet erosion and rill wash (e.g. Strömquist et al., 1985; Blong, 1985).

Blong et al. (1982) noted in Australia that more than half of the sediment produced in gullies came from erosion of the gully walls. Maximum erosion of the side walls was reached 20-40 years after the initiation of the headcut (Blong, 1985). The erosion rate, for a specific segment, then declines and the gully wall is stabilized and covered with vegetation. However, it is difficult to evaluate the importance of each individual process quantitatively in the field, since the overall sidewall retreat and headward advance reflects the total erosion. Also, some processes are effective throughout a rainstorm (e.g. rainsplash), while others are infrequent and build up for a potential failure (e.g. slumping of walls). The exception is the process of piping, which is easy to distinguish as being directly responsible for gully erosion where the pipe roofs have collapsed and created tributaries or headward extension of the main gully. After the collapse, regular gully processes aid in the further extension and expansion of the newly developed gully. At times plunge pool and piping erosion act together at the gully head. The surface runoff removes the material eroded from the tunnel. If the material is not removed, further development of the pipe is restricted.

Returning to the remark made in Section 2.2.1 on the Horton (1945) model of gully initiation, i.e. a sequence of sheet-rill-gully erosion down the slope. As we have seen, this is just one possibility of gully initiation. It may be observed on surfaces where runoff is concentrated, due to cattle tracks or other variations in the microtopography of the soil surface. The rill deepens downslope as velocity and erosivity of the runoff increase, and it eventually develops into a gully. Thus we have sheet, rill and gully erosion in a sequence downhill. However, as the gully head develops and migrates uphill it may engulf the rill and act as the collector of runoff. The rill has now been eliminated but was the actual initiator of the gully. The sheet eroded surface is found in conjunction with the gully. Another case where rills may be absent is when piping is present in an area and the pipes reach the soil surface giving rise to gully heads that collect the surface runoff. A third example is along gully edges where sheet erosion is often prevalent. The surface runoff may be collected at some point along the gully wall and initiate a tributary gully.

Several attempts have been made to classify gullies, based on outline, cross-section, source of runoff, location etc. Unfortunately no classification has yet been accepted as "universal", which is not surprising since the gully types vary with environment, and a shape or process described in one area may not apply to another.

Leopold and Miller (1956) classified gullies as continuous or discontinuous. Continuous gullies extend upslope from the main gully or drainage way, while discontinuous gullies start at any point on a slope as a headcut. The reason for the headcut can be a terrace, a cattle track or anything that provides a break in the soil surface or concentrates the runoff. The depth of the gully diminishes rapidly downstream and a fan of sediment is commonly found at the gully mouth (ibid.). The headcut will collect the runoff and the discontinuous gully extends upslope through headward erosion, and downslope through scouring. It eventually reaches the main gully and becomes continuous. Several discontinuous gullies on a slope may, if bedrock is not limiting, fuse together to form a continuous gully (Fig. 2.1).

Ireland et al. (1939) classified gullies on the basis of their outline. A linear gully is long and narrow with a narrow head and few tributaries along its sides. A bulbous gully is broad and spatulate in its upper end, but may be linear in its downstream portion. A dendritic gully has many branching tributaries. A trellis shaped gully has tributaries or branches that enter the main channel at angles approaching 90°. A parallel gully has two or more parallel tributaries which empty into a main gully. And, finally, a composed gully is a combination of two or more of the above mentioned gully forms.

The types of processes responsible for gully erosion in a small area is often reflected in the drainage pattern. A gully system developed by surface runoff will, under normal circumstances, give rise to a drainage pattern determined by bedrock and topographical conditions. Where the gullies have been initiated through human activities this may be reflected in the drainage pattern, e.g. along cattle tracks or road ditches. In soils prone to cracking and hence piping, the gully pattern, where the pipes reach the soil surface, is an image of the system of cracks and fissures in which the pipes developed. The drainage pattern may then assume a more trellised or rectangular shape.

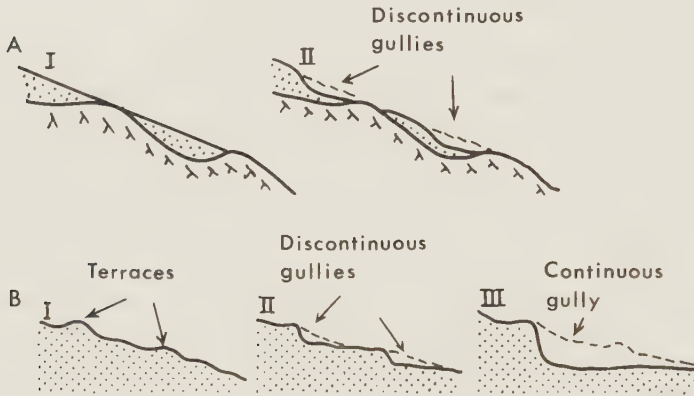


Figure 2.1. The development of discontinuous gullies. A: gully extension limited by bedrock, and B: gully heads at discontinuous gullies, initiated for example at terraces, fusing to form a continuous gully as extension continues.

De Ploey (1974) recognized three types of gullying. Axial gullying where the V- or U-shaped gully (cross-section) is marked by a single headcut (similar to Ireland et al.'s linear form). Digitate gullying, which is a complex gully form, retreats with several headcuts. Finally, frontal gullying with pedimentation where gullying starts from riverbanks and vertically stabilized gullies. The retreat is parallel to the slope and scarp.

Brice (1966) based his classification of gullies on their location in the drainage basin. A valley-bottom gully will eventually become a valley-head gully as its headscarp migrates into the valley head. Valley-slope gullies are independent of the valley head and result from less concentrated flow from different sources.

Gullies can also be classified by the shape of their cross-section. Basically they can be V- or U-shaped but there are also intermediate types. The shape depends on the resistance of the subsoil to erosion, and on the processes in action. U-shaped gullies form where the subsoil is deep and erodible. The upper part of the walls is close to vertical due to undermining and collapse of the banks. Along the bottom more or less remains of the fallen material, depending on the transporting capacity of the flow (Fig. 2.2 A). If the capacity is low a lot of material may remain along the gully sides, giving the gully a trapezoidal shape (Fig. 2.2 B). V-shaped gullies develop where the subsoil is relatively resistant to erosion (Fig. 2.2 C). Where downcutting reaches the resistant bedrock surface, or in places where sedimentation occurs in the gully bottom, the shape is rectangular (Fig. 2.2 D). Downcutting can, in the latter case, be initiated again to form a secondary gully in the bottom of the main gully (Fig. 2.2 E). A secondary V-shaped gully may also form if downcutting suddenly reaches a more resistant soil layer. Coarse sediment gives a wide shallow shape with low angle sides (Fig. 2.2 F). A V-

shaped gully may develop convex gully sides if sheet and rill erosion on the gully walls is extensive (Fig. 2.2 G). This is often the case where piping is present and has reached the soil surface. A resistant A-horizon above an erodible subsoil causes the upper horizon to form overhanging ledges (Fig. 2.2 H).

Imeson and Kwaad (1980) classified gullies according to their cross-section, the type of runoff, and the position in the landscape:

1. V-shaped; overland flow; anywhere in the landscape except valley bottoms.
2. U-shaped; overland flow; anywhere except valley bottoms.
3. U-shaped; subsurface flow; anywhere in the landscape.
4. U-shaped; overland and subsurface flow; exclusively in valley bottom positions.

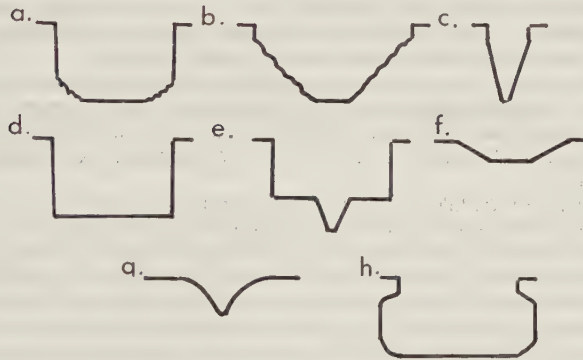


Figure 2.2. Examples of cross-sectional gully shapes (for explanation see the text).

2.4 Factors affecting gully erosion

This section will discuss how different factors indirectly or directly affect gully erosion.

2.4.1 Morphology of the drainage basin

The slope angle affects the amount and velocity of the runoff, the impact of raindrops on the soil surface, and the effect of sun radiation. More important is perhaps the effect of macro-topography on soil formation and development. The soils on flatter gradients may, for example, be more clayey and susceptible to desiccation cracking and therefore vulnerable to gully erosion through piping. Elevation and macro-topography of an area can have orographic effects on precipitation. Elevation may also limit the vegetation. The bedrock topography limits the fusion of discontinuous gullies, and can cause concentration of subsurface drainage lines leading to piping. The soil surface topography may provide depressions for infiltration and deposition, and concentrate the runoff.

The size and shape of the drainage basin may influence the area above the gully heads and, as a consequence, the amount of runoff collected at each head. The further the gully extends towards the drainage divide, the steeper the slope above the head and the more erosive the runoff collected at the head. But the amount of water is less and the soil gets thinner and thinner (i.e. less material available in which gullies can form), so the potential for gully erosion may nevertheless diminish and the erosion rate slow down as the head works its way upslope. In large drainage basins there may be differences in precipitation over the area. Hence, erosion rates can vary significantly from time to time in different parts of the basin. This is especially true in areas where rainfall is sparse and variable, or in areas where most of the rain falls in the form of concentrated thunderstorms.

The catchment area (i.e. area above each gully head) is considered to be the most important factor of those mentioned above in determining the rate of gully gully (Jepson, 1939; Thompson, 1964; Stocking, 1981).

2.4.2 Climate

The influence of climate on runoff generation and soil erosion in general has been discussed in Section 1.2 and the factors discussed there are also valid for gully erosion through surface runoff.

Temperature may affect gully gully by causing desiccation cracking which favours piping. This is accentuated on eroded lands which dry out to an even greater extent than areas covered with vegetation. Some of the rainfall factors discussed in Section 2.1 are worth mentioning again, as they have more direct effects on gully erosion.

The frequency and return period of intense and heavy rains are important. A very intense rainstorm may have initiated a gully which is further enlarged during less intense rains. Rains that not on their own would have been capable of initiating the gully. Even though the erosion then is carried out by storms of less intensity the damage was originally caused by a single heavy storm.

Marked seasonality of rainfall (i.e. marked wet and dry seasons) is not a prerequisite for piping, but has frequently been mentioned as being favourable (Downes, 1946; Downing, 1968; Parker, 1963; Crouch, 1976; Blakemore, 1978; Bryan and Yair, 1982). During the dry period the vegetation cover is reduced and the soils are subject to desiccation cracking, creating potential piping sites. The situation is similar in areas with highly variable rainfall during the wet and dry seasons respectively. A dry period during the wet season will have the same effect. Similarly, heavy rainfall on a clayey soil during the dry season, when the cracks are fully developed, may immediately initiate erosion in the cracks. Frequent rains keep the soil moist, and even if this makes the soil particles more easily detachable and reduces infiltration capacity, it has positive effects on the vegetation. In clayey soils the cracks and fissures are kept closed, preventing enlargement through erosion and pipe development.

High intensity rains are generally much more erosive than are long lasting, low intensity rains. It can be speculated, however, that low intensity rains would favour gully erosion through piping and tunnelling, allowing more water to infiltrate. On clayey soils, however, the clay minerals swell when wet and infiltration is restricted. High intensity rains result in quick filling of pore spaces in the topsoil leading to runoff in cracks etc., which may induce piping.

2.4.3 Geology and soils

The type of bedrock affects gully erosion indirectly by its influence on soil formation and soil type. More directly, the bedrock surface may act as an impermeable layer and initiate seepage and piping. In addition, if downcutting in a gully has reached the bedrock and the type of bedrock is resistant to erosion, further scouring is restricted. The flow in the gully bottom carries little sediment and is erosive. This is sometimes visible in the field where the soil pack is thin. The gullies which have reached the bedrock contain little or no debris along the side walls, indicating a high transporting capacity of the flow. Also, the roughness of the bedrock surface is usually less than that of the soil, which increases the velocity and erosivity of the flow. Hence, where bedrock is exposed in the bottom, sidewall erosion processes are very effective.

The characteristics of the soil in an area affects the rate of gully erosion in several ways. The effects on infiltration and erodibility were discussed in Section 2.1. A clayey, compact soil does not favour infiltration but is relatively resistant to surface erosion. Conversely a sandy, noncoherent soil favours infiltration but is also easily eroded if the flow is sufficiently erosive. The depth of soil and parent material may affect infiltration if the permeability of the bedrock is low. The depth is also important in influencing the rate of gully head cutting due to waterfall erosion. The chemical properties of the soil determine the amount of dispersion and therefore the susceptibility to piping. The nutrient availability affects fertility and hence vegetation.

It is appropriate at this point to give a more detailed description of the duplex soils mentioned in Section 2.2.2. They are highly erodible and their physical and chemical properties make them very vulnerable to piping.

Duplex soils are soils with a sharp textural change between an upper, coarser textured horizon and a lower, finer and clayey horizon (Faber & Imeson, 1982). This sequence can be found at several depths in the soil but is most obvious in the top layers. The A-horizon is leached by the percolating water and its clay particles eluviated. Reaching the less permeable B-horizon, the particles are deposited, clogging the pores and further enhancing the textural difference. Where duplex soils are mantled with a loamy A-horizon, and if they are properly managed, they can be relatively productive (Conserv. Div., 1979a). If the A-horizon is removed by erosion they turn into waste land. The upper (A) horizon, which has a more homogeneous structure and smoother surface than the blocky, aggregated B-horizon, is sometimes relatively resistant to surface erosion and forms a hardpan surface. It is often undercut by trickling water from surface runoff, forming overhanging ledges on exposed gully walls (*ibid.*). Due to the less permeable B-horizon the pore spaces in the A-horizon quickly become filled with water during rainfall. Additional water on the surface generates an overland flow which may become erosive. The difference in permeability causes an increase in hydraulic gradient which, in turn, may initiate subsurface seepage, piping or tunnelling.

A duplex soil can form *in situ* in two ways (Rooyani, pers. comm., 1985). Firstly through a normal pedogenetic process, where a shale acts as parent material. After weathering, the A-horizon is leached and its clay particles eluviated as described above. The second mechanism is through differential weathering, where the parent material consists of alternating layers of shale and sandstone. The different layers then weather into soil horizons of different texture. The two top horizons go through the same process as in the first case mentioned above.

Duplex soils can also form as a two-stage deposition of sediments (Conserv. Div., 1979a; Bishop et al., 1980). Reworked colluvial, alluvial, or aeolian material will in this case be deposited on top of an existing profile, which has lower infiltration and permeability rates. Le Roux and Roos (1983) suggest that a similar (duplex type) sequence may develop, without eluviation, through selective erosion of the top soil where the silt and clay fractions are removed, and the coarser fractions remain.

2.4.4 Baselevel

King (1951) and Chorley and Beckinsale (1968), among others, distinguished between two main types of baselevel. A grand baselevel defined as the extension of the sea level under the continents, and a local baselevel caused by local topographical or geological conditions. The use of the sea level as the ultimate baselevel can be debated, as noted by Beckinsale and Richardson (1964), since gravity forces and currents in the oceans may redistribute the material. The statement is, however, valid for fluvial processes with which we are concerned here. If channel gradients are in equilibrium with the base level, a change will ultimately lead to some kind of adjustment.

Tectonic movements, sea level changes and volcanic activity are all examples of processes that may upset the system. A lowering of the baselevel increases the gradient and erosion is required (degradation) to bring the system back to equilibrium. Conversely, a rise in baselevel results in a decrease in gradient and adjustment by deposition (aggradation) (Ireland et al., 1939). Pediplains (old erosion surfaces) are examples of temporary baselevels (Strahler, 1975). Denudation is very slow and the pediplain acts as a baselevel for the mountains and valleys elevated above the level of the pediplain.

More locally, the baselevel may be determined for example by a local bedrock outcrop or temporary storage of sediment in a valley. Thus, theoretically the ultimate baselevel of a gully

system in a catchment may be the sea level. In reality, on a shorter time span, the gully system is more dependent on local baselevels, e.g. topographical and bedrock conditions.

Changes in baselevel that cause sudden gully erosion can thus be assumed to be of very local character. For example, a reservoir will act as an artificial lake and raise the base level, resulting in deposition at the gully mouths entering the reservoir. Conversely, if a dam fails, the local baselevel is suddenly lowered and degradation occurs. Another example is if downcutting of a main gully is halted during a period of time due to a resistant soil horizon. The gully may then be considered out of equilibrium with its local baselevel (i.e. the valley bottom). The low order gullies entering the main gully may, however, have adjusted to their local base level, i.e. the main gully floor (the resistant soil horizon). When erosion in the main gully reaches a less resistant horizon, rapid erosion occurs as it strives to achieve equilibrium. This in turn puts the tributaries in disequilibrium, and they too respond by rapid erosion. In this way periods of rapid erosion alternate with periods of stagnation as the system is brought out of its equilibrium and, by adjustment, returns.

But how far upstream do the effects of a change in baselevel extend? Few studies include actual measurements and the subject certainly merits further study. Leopold and Bull (1979) observed in a field experiment in Colorado that the effect of a small scale dam in a stream could be observed about 40 m upstream, the remaining 220 m to the divide were left unaffected. They concluded that: "A local baselevel determines the height of the longitudinal profile immediately upstream from it. It follows that each local reach of channel acts as a local baselevel for that part of the longitudinal profile immediately upstream. Whatever the nature of a local base level, its effects extend upstream only a limited distance and the effect dies out with distance." They further noted that through headcut feedback, a baselevel fall causing degradation may affect the stream for greater distances than a baselevel rise.

This implies that within a drainage system, a change in baselevel (e.g. a dam) can cause adjustment by aggradation in the lower reaches, while the upper reaches may be in equilibrium or degrading.

2.4.5 Vegetation

The effects of vegetation on runoff and piping were discussed, in Section 2.1 and 2.2.2 respectively. Vegetation is usually considered to protect the soil and to prevent gully erosion by reducing runoff velocity, increasing roughness of the soil surface etc. However, vegetation is not always protective. Depending on type and coverage, the vegetation may promote a concentration of overland flow and rill formation, or induce piping. Blandford (1981) noted that an increase in vegetation density caused an increase in the rate of gully erosion, and ascribed it to an increase in infiltration at the gully head, leading to high soil moisture content and a higher potential for slumping and failure. Lynn and Eyles (1984) noted that about 95 % of the gullies caused by piping in New Zealand are found under grassland, while only a minority is found under scrub and forest. They do not provide an explanation to this phenomenon. Piping under scrub and forest may be hard to detect, however. The dense network of tree roots strengthens the pipe roof and enables the pipe system to fully develop prior to collapse (Baillie, 1975).

2.4.6 Human Impact

Almost all the factors mentioned above can be affected, on a short or long term basis, by human activities. When it comes to gully erosion, we are concerned with the former, i.e. activities that show effects within a relatively short period of time.

The human impact on soil erosion in a drainage basin can be observed as changes in the erodibility of the soil, and/or erosivity of flow. Both can be achieved in different ways by different landuse. Some of the most common causes of gully initiation referred to in the literature are: overgrazing (e.g. Malde & Scott, 1977); cultivation (e.g. Nir & Klein, 1974); and stock routes and roads (e.g. Blong, 1970).

The immediate effects of grazing are depletion of vegetation, weakening of soil structure, and concentration of overland flow. The distinction between overgrazing and grazing is commonly known as the carrying capacity of an area, i.e. the number of livestock an area is able to support without a decline in the productivity of soil and vegetation resources (Sandford, 1983). The carrying capacity depends on food supply, water availability, type of

animal, and kind of livestock management (Denevan, 1967; Le Hou  rou, 1976). The food supply and water availability are mainly dependent on climate, the former also on elevation and soil type. The capacity may vary greatly from year to year in areas with variable rainfall.

The kind of management is also important. Severe overgrazing and trampling can, for example, be seen in the vicinity of water sources. Denevan (1967) suggests that unrestricted grazing is far less detrimental to the vegetation than when limited by fencing. Lundholm (1976) noted that non-domestic animals in their natural ecosystems follow a grazing cycle which hardly ever leads to overgrazing. When grazing is poor the ground is covered quickly, and vice versa. The grazing cycle of domestic animals should theoretically work in a similar fashion if livestock numbers are adjusted to the carrying capacity of the area. This is, however, very seldom the case in grazed areas with severe sheet and gully erosion.

Overgrazing reduces infiltration and surface roughness by reducing the vegetation cover. Trampling leads to compaction of the soil and weakening of the soil structure. This leads to increased runoff and erosivity of flow. Along stock routes the flow becomes concentrated and diverted, initiating rill and gully erosion. Murray-Rust (1972) noted two different gully patterns caused by overstocking in Tanzania: dendritic gullies in areas with sheet erosion, and linear gullies developed along stock routes. Reduced infiltration also results in less moisture entering the soil for plant use (Dregne, 1983).

Overgrazing can also have less immediate effects. Several authors (e.g. Sellers, 1977) have speculated that overgrazing (i.e. removal of vegetation) results in increased albedo, leading to radiative cooling, increased subsidence and finally reduced rainfall. Walls (1980) suggests that the removal of vegetation hinders the natural process of seeding and germination among the plants that remain. Furthermore, with the insulation gone, the soil is more exposed to heating and cooling, and subsequent desiccation cracking.

All in all, overgrazing is destructive to the land. Lundholm (1976), however, argues that a certain amount of grazing can have positive effects on the productivity of the land by quickly recycling and releasing nutrients tied up in the vegetation.

Soil erosion on cultivated land depends on the type of crop, the management and the conservation measures taken. Row crops may concentrate runoff leading to gully erosion while cover cropping will have a protective effect. Rainfall during planting or harvesting may cause severe damage to the unprotected soil. Elwell and Stocking (1976), for example, noted a peak in soil loss during December in Zimbabwe, due to high rainfall (the beginning of the rainy season) but low crop cover. A common strategy in preventing soil erosion from cultivated land is terracing. There are several types of terraces but the basic principle is to reduce the erosivity of the surface runoff by reducing the slope length, and in some cases slope gradient. The terrace may be built level to encourage infiltration and conserve moisture (bench type), or graded in order to intercept and divert the runoff across the slope at low angles (graded ridges) (Ramser, 1917).

Terraces are generally considered to be effective in reducing erosion (e.g. Bradford et al., 1978). This may be the case with sheet erosion. Gully erosion, however, is very often initiated in conjunction with terraces. During heavy rains the velocity of the runoff along a graded channel terrace increases and the flow may become erosive. This is often visible in the field, where a gully may follow a terrace for quite a distance. If the terrace becomes overfilled the flow may spill over the edge and cause a break in the terrace. The gully continues to erode downslope cutting through the fields below, and headwards through the field above. A discontinuous gully has developed.

An absorption terrace built to promote infiltration may also cause erosion. The water infiltrates and the subsoil becomes close to saturated. The soil is weakened and seepage may cause undermining and slumping, resulting in a break in the terrace. The depression may also become overfilled, in which case excess water will drain over the edge and initiate a headcut. In both cases the effects are the same as mentioned above. The increased infiltration also encourages piping.

Plough furrows, if not ploughed exactly along the slope contour, may concentrate the runoff and initiate gully erosion through surface runoff. Furthermore, Nir and Klein (1974) suggest that the high rate of gully erosion in an area in Israel was the result of the introduction of contour ploughing. By reducing the amount of runoff, the pattern of ploughing resulted in an increase of throughflow and piping. The increased infiltration reduced the erosion in tributaries of the lower order by allowing an increase in vegetation. As a result the higher order gullies were supplied with a lower sediment load and thus had a higher erosion potential.

Tillage also creates a compact plough pan in the soil, with low permeability (Dregne, 1983). Above this plough pan infiltration is temporarily increased and cohesion of the soil is reduced,

making it very vulnerable to erosion (Roose & Piot, 1984). In addition, tillage results in soil impoverishment. Normally the bare soil to some extent adjusts to the process of erosion by developing a protective bedload lining or erosional lag deposit as protection. Tillage destroys these layers and brings the fines to the surface. Hence the soil is deprived of clay particles and organic matter more effectively where repeated tillage is used (Moss & Walker, 1978).

Roads and cattle tracks etc. increase and concentrate the runoff; urbanization, concreting, and deforestation increase runoff, all eventually leading to increased gully erosion.

Other human activities can, in a less immediate way, initiate or increase gully erosion. The building of a dam or reservoir for irrigation or hydropower can have both negative and positive effects. The dam acts as a trap for sediment and water. The discharge downstream is therefore reduced but also carries less sediment. Due to this, the flow may still be erosive, especially in combination with floods when the capacity of the dam is exceeded. Upstream, the dam causes a raised baselevel which results in deposition at the nearby gully mouths. Furthermore, the water in the dam may cover the most suitable crop land in the drainage basin. This loss will have to be compensated for by the opening up of marginal lands which may be more susceptible to erosion. The dam also provides a local supply of water that would otherwise not have been available, resulting in increased stock numbers and overgrazing (Murray-Rust, 1972).

2.5 The concepts of thresholds, cyclic erosion and equilibrium

Rao (1978) defined "threshold" simply as "the point at which a stimulus initiates a response". Schumm (1973) recognized two basic types of thresholds:

- **extrinsic:** the threshold exists within the system but will not be crossed without the influence of an external variable.
- **intrinsic:** a progressive change within the system itself causes the crossing of the threshold.

He further defines a threshold specifically connected with landform stability and geomorphic systems:

- **geomorphic:** a threshold of landform stability that is exceeded by changes either in external or internal variables (i.e. changes in climate, soils, relief, landuse etc.).

Once a threshold has been crossed the system immediately strives to reach a new state of equilibrium and stability. Schumm (1973) referred to this as "complex response". The event that triggers the response does not necessarily have to be geomorphologically significant, the result depends on the state of the system. Hence, if the potential is close to the threshold value, an insignificant event may cause the crossing of the threshold. Conversely, high magnitude events may cause drastic changes even if the potential at the moment is far from its critical value.

Tanner (1968) defined equilibrium (or steady state) as existing when the material, processes and geometry of a system form a self-correcting balance. Howard (1965) defined it as "a complete adjustment of internal variables to external conditions". A change in an external variable will force the system to adjust to the new regime. Due to the size and mass of geomorphic systems there is a time lag before a system responds to a change in input (op cit., 1982).

Karcz (1978) related stability within a system to its response to fluctuations. In a stable system, the fluctuations caused by a disturbance are dampened, in an unstable system they are amplified and in a neutral system they are neither dampened nor amplified.

Moss and Walker (1978) defined a landscape as stable when it can withstand erosional and depositional events without significant hydraulic adjustment. The surface may remain unresponsive for long periods, but meanwhile the need for adjustment increases. The system thus builds up a potential for erosion. Adjustment finally occurs when a critical point has been reached. They referred to this as "stored hydraulic potential".

The concept of definite equilibrium or steady state should only be considered as a ideal model. If defined as a static condition, no natural system will ever achieve equilibrium. It is a matter of scale, both in time and space. Schumm and Lichty (1965) recognized three different time scales, "steady time" (days) which is a part of "graded time" (100-1000 years) which in

turn is part of the "cyclic time", and suggested that certain components of a drainage basin may be considered to be in equilibrium during "steady time" but not the whole system.

Tanner (1968) stated that short time changes must be excluded from any equilibrium and gave the example of a sand dune which must have an equilibrium form on a time scale in which short term fluctuations (daily, seasonal) are averaged out. The term "quasi-equilibrium" as introduced by Leopold and Maddock (1953) may be more appropriate. It can be defined as a state of near equilibrium where absolute equilibrium is never reached because of constant changes in the energy environment.

The concept of cyclic erosion was introduced by Davis (1899). He used it to explain the large scale denudation of the earth crust, followed by uplift and rejuvenation. The idea has since then been modified and extended to apply to smaller scale processes.

Schumm (1977) recognized five cycles of different dimensions:

1. Cycles associated with tectonic movements.
2. Cycles associated with isostatic adjustment or climatic change.
3. Cycles related to the crossing of geomorphic thresholds.
4. Cycles of smaller dimensions caused by attempts of the system to adjust to changes related to 1-3.
5. Cycles related to the seasonality of hydraulic events.

Whatever the scale or periodicity of an erosion cycle, the pattern is the same, with periods of relative equilibrium separated by periods of some type of instability (erosion or deposition). There is usually some type of threshold involved that has to be crossed before a period of instability can be initiated. Ireland et al. (1939) identified an erosion cycle in connection with gully erosion as: 1. channel cutting (natural or induced); 2. downward scouring and plunge pool erosion; 3. readjustment (as the head migrates upslope); and finally 4. stabilization. Increased runoff may then reinitiate gully erosion and the cycle starts again. Similar sequences of events have been suggested by Bishop (1962), Blong (1970), Nir and Klein (1974) and Tejuwanj (1975), among others. The erosion cycle is rejuvenated when a geomorphic threshold is transgressed due to increased erodibility of the soils or increased erosivity of the runoff (Imeson & Kwaad, 1980).

The existence of different kinds of thresholds in the geomorphic environment is well known. A classic example is the Hjulström (1935) curve defining the velocity of flow needed to entrain particles of different sizes. Other examples include snow avalanches and landslides, or rainfall exceeding the infiltration capacity of a soil.

Several authors have reported on thresholds in connection with gully erosion. A number of factors and variables affect gully erosion and the thresholds of different processes form a very complex pattern, controlling and interacting with each other. Schumm (1973) identified a critical valley slope above which the valley floor is unstable and gullies can form. Patton and Schumm (1975) added the factor of drainage basin area, the larger the area, the lower the necessary slope to initiate gully erosion. Graf (1979) studied the relationship between vegetation on the valley floor and tractive force. When the resistance is exceeded, gully erosion is initiated. He also defined thresholds for channel roughness, gradient and width. Stocking (1981) discussed several processes leading to gully erosion where he considered thresholds to be involved. He gave the example of an intrinsic threshold as when a roof of a pipe collapses and results in a gully.

3 GULLY EROSION IN LESOTHO

3.1 Geographical background

3.1.1 Morphology

Lesotho is a small, mountainous country with an area of 30 355 km² at an altitude ranging from 1 500-3 400 m above sea level. The country can be divided into two physical provinces (Bawden & Carroll, 1968): the mountain province which covers 2/3 of the country mainly in the east, and the lowland province which is found in the west (Fig. 3.1). The two provinces are separated by the foothill region. In the south-east, the Orange River valley constitutes a slightly different and intermediate landtype. The provinces can then be further divided into 27 different land systems. The areas studied are situated in the lowland parts of the districts of Leribe, Berea, Maseru, Mafeteng and Mochale's Hoek. For convenience, the tables and graphs in the following sections only show data from these districts and for Lesotho as a whole.

3.1.2. Climate

Schulze (1947) made a detailed map of the climate of South Africa (including Lesotho) based on the Köppen classification system. The climate in Lesotho is classified as temperate, characterized by warm, moist summers and cold, dry winters (Cwb). Mean annual temperature is about 15°C in the lowlands with winter temperatures frequently dropping below zero at night. The wet season is generally considered to last from October through April (Berding, 1981). The average annual rainfall varies from just under 500 mm in some sheltered valleys in the mountains, to about 1 400 mm for some stations with orographic effects in the mountains (Fig. 3.2)(De Baulny, 1980). The rain falls in the form of high-intensity thunderstorms, or low-intensity frontal drizzles. Almost half of the rainfall is received in storms of 10 mm or less (Berding, 1981).

There are few automatically recording rain gauges in Lesotho and the records are limited in time and frequently irregular. Values of rainfall intensity are therefore rare. The longest records of rainfall intensity available are for Maseru and Oxbow (northern mountains) running from 1964 and 1959 respectively for which average EI-30 values have been calculated and published. The average annual EI-30 values are 115 and 57 respectively (Scherer, 1978). The EI-30 value is a dimensionless index calculated as the product of rainfall energy (E) and the maximum amount of rainfall received during a 30-minute period converted to intensity in mm/h (I-30)(Wischmeier and Smith, 1978). The index can be seen as a measure of rainfall erosivity. Smithen and Schulze (1982) made a map of average annual EI-30 for South Africa in which Lesotho is included (Fig. 3.3). They used some of the rainfall stations in Lesotho and several stations in the border regions of South Africa and extrapolated the isolines over Lesotho. A large part of the central mountains has been excluded due to insufficient data. The map is very rough and should be treated with caution. Nevertheless, the map supports the general view that rainfall erosivity, in the lowlands, decreases towards north.

The evaporation in the lowlands of Lesotho is around 2 000 mm (Class A pan; Binnie & Partners, 1972a), and hence there is an annual water deficit. Still, the mean values of important climatic factors, i.e. temperature, evaporation and precipitation, are all sufficient for good agricultural production (Min. of Agric., 1986a). The problems are related to the variability and deviations from the average, e.g. hailstorms, early frost, heavy rainfall, and drought. Longterm records show that the annual rainfall may vary by as much as 50 % from the mean (ibid.). In areas with relatively low annual rainfall, negative deviations may easily become critical. The variability of rainfall also causes wide fluctuations in range productivity, and consequently in the carrying capacity of the pastures.

Tyson and Dyer (1975) analysed meteorological data for the summer rainfall region in southern Africa since 1910. They concluded that there is an oscillation of 18.65 years between 9-10 year long wet and dry spells, i.e. periods when, on an average, there is less than normal rainfall and vice versa. In addition, they detected 2 shorter oscillation periods of 2.35 and 3.65 years that contribute to the annual deviations. Tyson (1981) suggests tentatively that the longer oscillation is linked to the fluctuations in the position of the subtropical highs of the Atlantic and Indian Ocean for which a 19-year oscillation period has

been found. Annual variations within the dry or wet spells do exist, i.e. a dry year within a wet spell or the opposite. Eckert (1982) compared Tyson and Dyer's suggestions with the rainfall in Lesotho since 1910 and concluded that the pattern also applies to Lesotho. The pattern was less pronounced in earlier years and "the presence of counter-cyclical years is more frequent in the earlier portion of the record" (*ibid.*, p. 7), i.e. the spells, wet or dry, are becoming more homogeneous.



Figure 3.1. Lesotho with districts and provinces. The locations of the study catchments are indicated. The meteorological stations referred to in the study are situated in the towns of Leribe, Maseru, Mafeteng and Mochales Hoek (after Dir. of Overseas Survey 417 (Misc) E 1967, as published in Bawden & Carroll, 1968).



Figure 3.2. The distribution of mean annual rainfall over Lesotho (after De Baulny, 1980).

The implications of this 20-year oscillation on soil erosion are that the dry spell will cause a general degradation of vegetation cover and a decline in crop yields, making the soil more vulnerable to erosion when the wet spell starts. A similar result will be reached if there are deviations within the dry and wet spells, e.g. a wet year in a dry spell. On a shorter time scale, the equivalent is the occurrence of monthly extremes during a year, e.g. an extremely wet beginning of the wet season (October-November), or an unusually dry month within the wet season.

3.1.3 Geology and soils

The bedrock geology is characterized by a sequence of near horizontal sedimentary strata (Fig. 3.4), which are topped by layers of basalt in the mountain province. The sedimentary strata outcrop in the lowlands at different altitudes, forming escarpments. The escarpments consist of steep debris slopes under a resistant bedrock layer with gently sloping planation surfaces above (Schmitz, 1984). The country is crossed by dolerite and kimberlite dykes which sometimes cut through the whole sequence of strata, and sometimes die out within the basalts (*ibid.*). The different geological formations have given rise to the different soils of Lesotho. The soils are described in detail in "Soils of Lesotho" (Cons. Div., 1979a) and in Cauley (1986), from which the information in the following three paragraphs originates.

The classification is based on the USDA (1975) system and has six categories: order, suborder, great group, subgroup, family, and series. The different soil series occur in individual and characteristic patterns, soil associations. The associations bear the names of the major series, listing the series in descending order of prominence or extent. For

convenience, the local names of the soils will be used in this study, the local and corresponding scientific names are listed in Appendix 1.

The mountain and foothill areas consist of volcanic rock (basalt), i.e. the Lesotho Formation. The rocks are moderately weathered and have given rise to dark coloured and favourably structured, neutral soils, the Fusi, Matsana, and Popa series. Soils developed from the Clarens Formation (sandstone) are found on the plateaus overlooking the lowlands. They are sandy, light or dark coloured, and strongly acid soils, e.g. Ntisi and Matela. Below the escarpment, on the true lowland portion, soils are found that have developed from fine subsoil materials derived from the Molteno and Elliot Formations (mainly sandstone and shales), and alluvial and colluvial sediments. Among these soils are found, for example, Majara and Maseru dark variant, as well as the soils of a duplex nature. Gully erosion in Lesotho is not limited only to the duplex soil types but, as mentioned in Sections 2.2.2 and 2.4.3, these soils are very erodible and particularly vulnerable to gully erosion and therefore merit a more detailed description.



Figure 3.3. Isolines of annual EI-30 values (i.e. rainfall erosivity) over southern Africa (after Smithen & Schulze, 1982).

Conservation Division (1979a) recognized and described five duplex soils in Lesotho: Tsa'kholo, Patsa, Maseru, Sephula, and Tsiki soil series. Cauley (1986) added Moshoeshoe to this group. They are typically lowland soils found along valley bottoms and characterized by extensive gully systems. The Conservation Division (1979a) estimated that the duplex soils cover about 6 % of Lesotho's total area and about 20 % of the lowlands. The textural difference between the A2- and B-horizons is due to the high content of clay in the latter. In all but the Tsiki series this exceeds 35 %. Tsiki soils have less clay but a high silt content giving rise to a less dramatic but still marked textural change. Bulk densities of all horizons of duplex soils are higher than those found in non-duplex soils. This indicates lower porosity and consequently lower infiltration and permeability rates. The infiltration rate, however, varies from season to season. During the dry season the permeability of the B-horizon tends to rise because the structural aggregates shrink, and therefore the infiltration rate is largely dependent on the porosity of the A-horizon. During the wet season the soil becomes water logged and the almost impermeable B-horizon causes the build-up of a perched water table resulting in lateral drainage downslope, on the surface or in the A-horizon. The Sephula, Maseru, and Tsiki series have a much lower exchangeable sodium percentage (ESP; see Section 2.2.2) (less than 15) than Patsa and Tsa'kholo (more than 15). The latter two are the only real sodic soils in Lesotho (Rooyani & Badamchian, 1986) and would therefore appear to be more vulnerable to piping. There is a dominance of illitic clays in the lowland and duplex soils, and of montmorillonitic clays in the mountain soils.

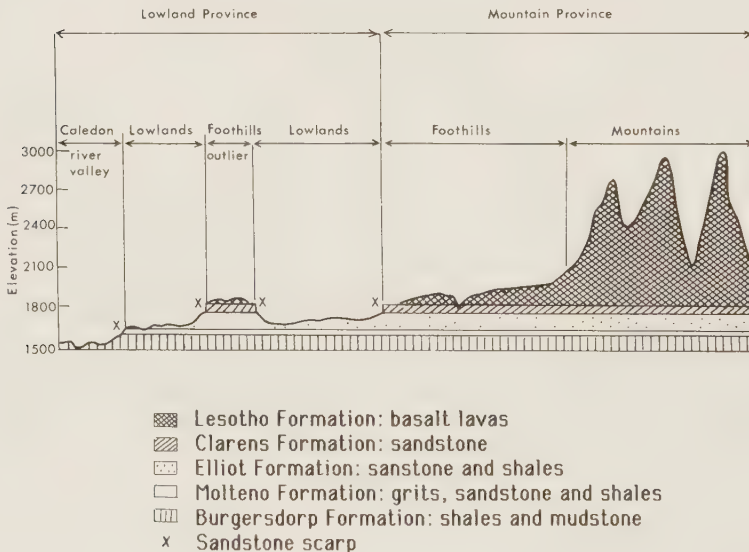


Figure 3.4. Geological transect of Lesotho (after Binnie & Partners, 1972b).

3.1.4 Vegetation

The natural vegetation of Lesotho is grassland (veld) of different types. Native trees are rare but can be found in scattered locations along the major rivers and in the Senqu River valley. Exotic tree species have been and are being introduced in plantations. Bawden and Carroll (1968) distinguished six vegetation mapping units for Lesotho:

1. **Themeda-Cymbopogon-Eragrostis grassland**, covering most of the lowlands south of Leribe District, and the Senqu River valley. The grasses are sweet or semi-sour and dominant species are e.g. *Themeda triandra*, *Cymbopogon pliriodis*, and *Eragrostis* spp.
2. **Themeda-dominant grassland**, covering the western-most part of the lowlands. *Themeda triandra* is almost totally dominant.
3. **Themeda-Festuca grassland** in the foothills and on the lower mountain slopes. Dominant grasses are again *Themeda triandra* and *Eragrostis* spp., at higher elevations (2000 m) joined by *Festuca* spp.
4. **Alpine grassland** in higher mountain areas. Dominant grasses are e.g. *Festuca* spp. and *Danthonia disticha*. *Themeda triandra* is still common but of minor importance.
5. **Highland scrub** on rocky slopes in sheltered valleys along the Senqu River valley and the northern-most foothills. Here patches of bush can be found, mainly *Leucosidea sericea*, *Rhus* spp., and *Olea* spp.
6. **Grassveld-highland scrub transition** type vegetation is found in the more humid northern lowlands and part of the foothills. Dominant grasses are e.g. *Themeda triandra*, *Eragrostis* spp. and *Tristachya hispida*. Patches of bush, e.g. *Rhus* spp., are found on the rocky slopes.

Acocks (1975) made a survey of the veld types of South Africa (including Lesotho), and the past, present and future development of these. The present vegetation pattern in South Africa (and Lesotho) is a result of vegetation migrations during millions of years, caused by climatic changes, and by human activities (within the last 100-200 years), the latter mainly through the introduction of domestic animals and the resulting selective grazing, i.e. overgrazing in areas with palatable vegetation. This has resulted in a change in species composition where palatable species are replaced by less palatable ones (in humid areas) or, worse, not replaced at all. The Themeda/Cymbopogon veld type is particularly vulnerable to overgrazing (ibid.). In addition to reduced vegetation cover the resulting poor condition of the veld renders it a much lower water use efficiency and it is therefore subject to drought despite adequate rainfall (Snyman & van Rensburg, 1986).

According to Acocks (1975) this degradation has caused the reversal of the natural migration of tropical veld types from the north. Instead there is a rapid advance towards the east and north-east of the westerly semi-arid veld type, the Karroo, leaving behind it desert or semi-desert. Christopher (1982) claims that this extension of desert-like vegetation is entirely due to mismanagement of the land and does not reflect a change in climate. It is probable, however, that soil erosion and degradation have caused a decline in soil moisture, thus creating "desert-like" soil conditions. Acocks (1975) speculates that, if the present degradation is allowed to continue at the same rate, by the year 2050 the Karroo veld will have covered all of Lesotho except the northern lowlands. This area will be in a transitional stage and still be able to support a grass veld, but of a poorer type than at present.

Pim (1935) in the early 30s noted the "invasion of the bitter Karroo" (an unpalatable shrub, *Chrysocoma tenuifolia*) in Lesotho. Jacot Guillarmod (1971) made a more detailed survey and noted that the heavy grazing has led to the replacement of palatable grasses by invaders such as *Cynodon dactylon* and *Senecio asperulus* in the lowlands; shrubby plants like *Felicia filifolia* and *Chrysocoma tenuifolia* in the foothills; and e.g. *Harpechloa flax* and *Aristida* spp. in the mountains.

3.1.5 Population and landuse

Due to the steep slopes and high altitudes, it has commonly been claimed that only about 10- 12 % of Lesotho are available and used for cultivation (e.g. Morojele, 1963a; Bur. of Stat., 1972, 1988). The most recent figures from the Range Management Division (Makhlelebe, pers. comm. 1988) show, however, that 34 % is used for cultivation. If this increase is due to an increase in cultivated area or an improvement in the methods used when estimating the area, is not clear. "Modern" farming in Lesotho started in the beginning of the 19th century (Morojele, 1963b). Shifting cultivation was practised in the mid-1800s, but as the population increased it had to be abandoned (Germond, 1967). By 1875 about 8 % of Lesothos total land area was estimated to be under cultivation (Anon., 1878), and at the turn of the century virtually all arable land in the country was being used:

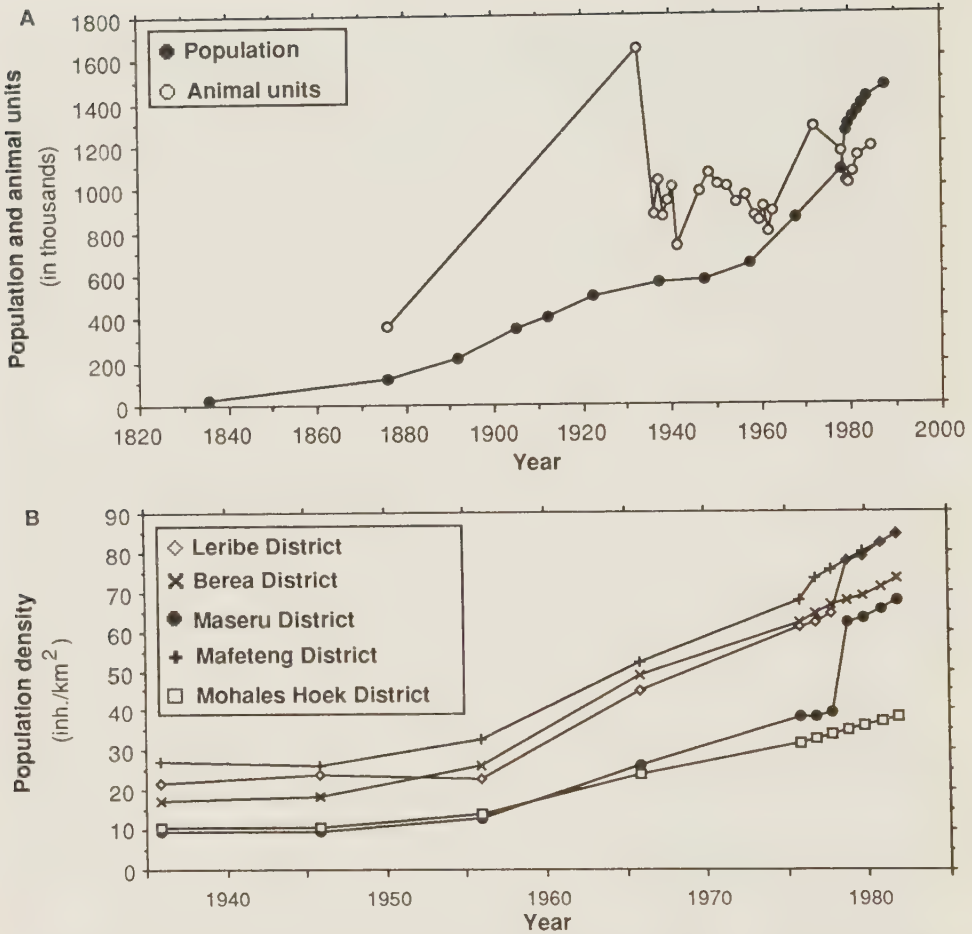


Figure 3.5. A: population and animal units in Lesotho 1835-1986, and B: population densities by district. One animal unit equals 1 cow or horse, 1.25 donkey or mule, 5 sheep or goats (Brokken et al., 1986)(sources: Anon., 1878; Pim, 1935; Germond, 1967; Statistics Section, 1962; Bur. of Statistics, 1965, 1966, 1972, 1976, 1983, 1987a, 1988). In 1979 a new district was created, Thaba Tseka, in which areas in the mountains of the Leribe and Maseru Districts were included. The areas lost are less populated than the lowland areas, hence the sharp increase in population densities between 1978 and 1979 for these two districts.

"With the uninterrupted growth of the population, the arable fields have progressively invaded the territory formerly reserved for the pasture. Today, agricultural lands form a continuous carpet over the whole plain. They have reached the mountain-sides and generally extend into the rocky fringe beyond which organic soil is lacking. Even on the mountain-summits, wherever a plateau may be found, they have marked their fields and, as the population has continued to increase, now ask themselves where they are to find arable land." (Bianquis, 1909; as cited in Germond, 1967, p. 410)

It is beyond the scope of this study to provide a detailed analysis of the economical development of Lesotho's agriculture, but a brief summary may be relevant for the discussion in Section 5. Up to about 1920 Lesotho had a net export of grain, mainly to South Africa

(Murray, 1981), but since then there has been an increase in net import. Apart from population growth, the reasons for this reversal are, for example, droughts, the development of the railways and the arrival of cheaper American and Australian grain in South Africa (*ibid.*). Furthermore, Lesotho lost a major part of its productive lowlands to South Africa in 1868 (Parsons, 1982; Min. of Agric., 1986b).

In 1986 the population of Lesotho was just under 1 500 000 (Fig. 3.5) (Bur. of Stat., 1988) and the number of rural households totalled around 280 000, with an average area under cultivation of about 1 ha/household (Bur. of Stat., 1987c). Mechanical farming implements such as ploughs and planters are relatively common. In 1875 just under 3 000 ploughs were in use in Lesotho (Anon., 1878). The figure had increased to about 15 000 in 1900 (Min. of Agric., 1986b), and to about 58 000 in 1970 (Bur. of Stat., 1972). Tractors are rare, however, only about one tractor in 100 households was registered in 1984 (Bur. of Stat., 1988). The use of fertilizers is low but increasing and in 1984 the average was 45 kg per hectare planted (Bur. of Stat., 1985). Fertilizers have been and are used much more in the northern lowland districts, the use declines towards the south (Morojele, 1963c; Bur. of Stat., 1972; Khanyane, Lesotho Co-op, pers. comm., 1988). Fallowing as a method for restoring fertility is not widely practised in Lesotho. The fields that are left in fallow are rather a result of a shortage of labour and farming implements to work the fields at the time of planting, or that the spring rains necessary for planting are delayed (Makhanya, 1979).

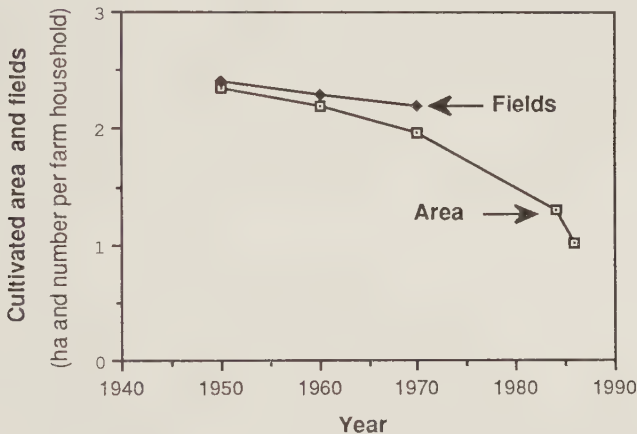


Figure 3.6. Average size of land holding and number of fields per farm household 1950, 1960, 1970, 1984 and 1986 (sources: Morojele, 1963a; Bur. of Statistics, 1972, 1985, 1987b).

The traditional system of land allocation gave the chief the power of allocating no more than three fields to every married man for lifelong tenancy. The fields were spread out in order to give the farmers equal shares of good and poor land, and to minimize climatic hazards such as hail and frost (Min. of Agric., 1960). If the land was left in fallow or neglected for more than two years, it could be taken away from the individual and reallocated (Min. of Agric., 1986a). This was also the case if the farmer produced more than the household required for subsistence, then a portion of the land might be reallocated (Wellings, 1986).

With the increasing population, this system led to land fragmentation and declining size of land holdings (Fig. 3.6). Furthermore, it was discouraging to progressive farmers. The Land Act of 1979 introduced a new system, whereby land can be held by lease, license or allocation. The most important implication is probably the removal of the chief's power to reallocate land, and thereby penalize successful farmers. The land can also be inherited by the oldest son or a person nominated by the surviving members of the family. This will prevent further fragmentation (*ibid.*).

The staple crops in Lesotho are maize, sorghum and pulses. In the lowlands, planting is carried out in October-November and harvesting in May-June (Min. of Agric., 1986c). Sorghum is more drought resistant than maize and regions that receive less than 500 mm of rain from October to March are considered unsuitable for maize production (Berding, 1984a). Yields are dependent on climatic factors, soil conditions and fertilizer input, and are declining despite an increase in fertilizer use (Fig. 3.7). The most commonly used domestic grazing animals are sheep, goats, cattle and horses. The animals are used for food, as a form of investment, for draught power and transport, and for social purposes and obligations. Most of the animal manure is used for fuel, not for spreading on the fields. Communal grazing is practised but a grazing permit, issued by the chief, is now needed to be allowed access to the communal lands (van de Geer & Wallis, 1984).

After the harvest of maize and sorghum in April-June, the livestock is brought back from the summer pastures in the mountains, and the stubble left in the cultivated fields is grazed during the winter months. This prevents the farmers from planting winter crops in the fields, or leaving crop residues as green manure (Wellings, 1986). Table 2 shows the most recent estimates of carrying capacities for the different districts in Lesotho according to the Range Management Division (Makhlelebe, pers. comm., 1988). Unfortunately no accurate estimates have been made prior to their investigation. It is probable however, that the carrying capacity of Lesotho's rangeland has declined due to invasion of unpalatable grasses and shrubs and that it was slightly higher during the beginning of this century. Nevertheless, Lesotho is and has been overstocked since the end of last century. The term overstocked can be debated, however. The stocking rates (ha/animal unit) are based purely on rangeland productivity, but since the animals feed on stubble all winter, Lesotho as a whole can probably support more stock than indicated by the carrying capacity (Makhlelebe, pers. comm., 1988). This is probably the reason why Lesotho can be continuously overstocked. Nevertheless, even if Lesotho is not as "overstocked" as the figures indicate the ranges are and have been heavily overgrazed for a long period.

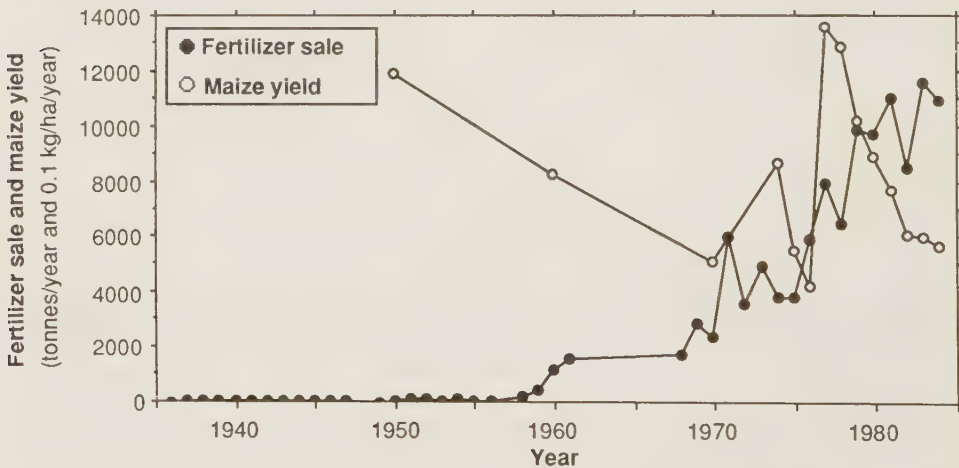


Figure 3.7. Annual fertilizer sale and maize yield in Lesotho since 1950 and 1936 respectively. No statistics on fertilizer use in kg/ha are available prior to 1970, therefore the amounts of fertilizers sold are presented (sources: Morojele, 1963c; Bur. of Statistics, 1972, 1984, 1985, 1987c; Masia, 1976).

According to some historical letters quoted in Germond (1967) the spreading of rinderpest in 1896 and the drought of 1897 severely decimated the number of livestock (Fig. 3.5), and the pastures had time to recover to some extent during the following wet years. During the next 30 years veterinary services were introduced against rinderpest and sheep scab (Morojele, 1963d), which, in combination with high wool prices, caused the livestock population to increase sharply and reach its peak in 1930. The world-wide depression and

severe drought of 1930 led to a new crash (Pim, 1935) from which the livestock population has not yet fully recovered. This is a little surprising since the human population has just about tripled since 1935 (Fig. 3.5). Tiedeman (1983) suggests that the stocking rate in Lesotho has reached a new, lower, equilibrium after 1930. The drought and overgrazing before the crash led to such severe exhaustion and degradation of the pastures that Lesotho's rangeland can no longer maintain the equilibrium at the 1930 level. Imports of livestock may well push the stocking level beyond the new equilibrium, causing the equilibrium level to drop even lower (ibid.).

Table 2. Recent estimates of arable land, range land, carrying capacity and stocking rate, by district and for Lesotho (Makhlebe, Range Management Div., pers. comm., 1988). The catchment Maseru 2 is situated in the Berea District.

District	Arable land (%) (1)	Rangeland (%)	Carrying capacity (animal units) (2)	Stocking rate (ha/animal unit)	Actual No. of animal units 1983 (3)
Leribe	33	63	23 903	8.1	146 850
Berea	51	43	11 039	7.9	140 775
Maseru	40	57	33 103	7.3	135 000
Mafeteng	58	37	6 825	8.8	126 800
Mohales Hoek	40	59	19 921	11.4	107 925
Lesotho	34	64	279 081	7.9	1 166 805

(1) Earlier estimates give a total arable area in Lesotho of 9-12 % (e.g. Morojele, 1963a; Bur. of Statistics, 1972, 1988).

(2) One animal unit=1 cow=1 horse=1.25 donkey/mule=5 sheep/goats (Brokken et al., 1986).

(3) Bureau of Statistics, 1987a.

Where the slope angle is not a limiting factor, virtually all soil types in Lesotho are being cultivated, including the very erosion prone duplex types. The unsuitability of these soils for cultivation lies in the severely restricted rooting depth (due to the clayey subsoil), the slow permeability and poor drainage (Cauley, 1986). The organic matter content is low and the natural fertility is rated as low to moderate (ibid.). In general, the mountain soils, derived from basaltic rock, have a much higher fertility status than the lowland soils, derived from mud-, silt- and sandstone (Rooyani & Badamchian, 1986). The most appropriate use for the duplex soils, to avoid erosion hazards, is to keep them under a dense and permanent grass cover. The prospect of keeping 20 % (the area covered by duplex soils) of the arable land in the lowlands under permanent grass cover is obviously unrealistic, since all of it has to be used to feed the growing population. Meanwhile, the problem of gully erosion on the duplex soils persists.

3.1.6 Soil erosion and conservation - past and present

Historical records show that soil erosion in Lesotho is not only a recent phenomenon. On the contrary, it seems that the problem of land degradation became apparent in the mid 1800s, and was in certain locations severe as early as the turn of the century. Germond (1967) translated and assembled letters and diaries from missionaries and travellers in Lesotho from 1829 and up to the beginning of this century, notes that include several recordings of soil erosion. They are almost solely of gully erosion, but, to a certain extent, these observations may be biased, as sheet erosion is harder to detect and less obvious than gully erosion. It is impossible to draw any quantitative conclusions from the records, but, nevertheless, gully erosion has existed for at least 150 years. The following quotations from Germond (1967) will serve as examples of gully erosion and land degradation:

"This country is dissected by deep ravines which lead to the Caledon which is even deeper." (p. 54, F. Maeder, 1842)

"... the sight of the deep ravines which traverse Basutoland (i.e. Lesotho) in every direction and which continue to grow from year to year progressively draining and desiccating the most fertile parts..." (p. 410, L.S. Duvoisin, 1858)

"Fifty years ago these ravines were extremely rare and almost unknown, today they rend and lacerate the entire landscape; they are found in every direction, two or three in the course of an hour and their rate of growth is terrifying." (p. 408, F.H. Kruger, 1882)

"The plateau of Teyateyaneng, Sefikeng, Berea and Thaba Bosiu is not uniform. Apart from the deep indentations, which appear in our map, there are numerous crevasses which have been enlarged by erosion." (ibid.)

"Soon the country will no longer suffice for its inhabitants: the population increases considerably from year to year; the fallow shrinks in the same proportion and at the same rates as the pastures. More than half the fields have been under continuous cultivation for half a century and are exhausted; the wheat is wilting." (p. 471, P.F. Ellenberger, 1890)

There are even indications of cyclic gully erosion and reinitiation:

"... at the bottom of the gully a new crevasse is forming, six feet wide and three deep. It is here that the puny rill continues to flow, a tiny trickle which, when swollen by storm waters, is converted into a turbid torrent and continues its career of devastation." (p. 408, F.H. Kruger, 1883, Berea Mission)

Balfour (1885), however, made a note of gully growth in actual figures from the Berea Mission:

"... the whole of its growth is the work of fifty years. It is now, we guessed, about 80 feet deep and 150 feet wide." (p. 48)

In the literature, the common causes for erosion in Lesotho referred to are increasing population, agriculture extending into the foothills and marginal lands, increase in livestock numbers etc. (e.g. Pim, 1935; Morojele, 1963:d; De Geer & Wallis, 1984). Potter (1982) estimated that 2 % of the arable land surface in Lesotho is being eroded away every year. In the mountain and foothill zones, erosion occurs mostly in the form of sheet and rill erosion. These forms of erosion are also prevalent in the lowlands, in addition to extensive gully erosion.

Pim (1935) estimated that 10 % of the arable land in the lowlands was threatened by existing dongas. According to the Agricultural Census (Morojele, 1963:c) as much as 8.8 % of the arable land of the lowlands was severely affected by gully erosion in 1960. In addition 25.5 % was slightly affected. The census further divides the lowlands into two parts, separating the "lowlands proper", from the "border lowlands", i.e. the western-most triangle of the lowlands (covering the western half of Mafeteng District and the north-western part of Mochale's Hoek District). The border lowlands was the most severely affected part of the lowlands. No less than 20.7 % (!) of the arable land was severely affected by gully erosion and 35.5 % slightly affected. The corresponding figures for the foothills were 14.7 % and 23.9 %, and for the mountains 8.2 % and 29.5 %. According to the census, gully erosion would appear to be just as common in the mountains as in the lowlands (all lowlands), but it should be noted that the figures are solely for arable land and the percentage of arable land is much less in the mountains and the foothills than in the lowlands. Conservation Division (1979a) estimated that 150 km² (0.5 %) of the whole of Lesotho was affected by gully erosion.

Chakela (1987) made a survey of the erosion hazard in Lesotho. The whole country was divided into grid squares covering 14 x 14 km (1/4 of a sheet of the topographical map 1:50 000). For each square an erosion hazard unit was determined based on four factors: vegetation cover, mean slope, soil erodibility, and mean seasonal rainfall energy. The

resulting map (Fig. 3.8) does not show the existing erosion but the hazards of rapid degradation, if the land is not carefully managed. Very high values were obtained for the mountains and foothills due to generally high values of precipitation (even though the rainfall is less aggressive than in the lowlands), steep slopes and thin soils. The border lowlands have a lower erosion potential due to lower rainfall and slopes. Thus, the erosion hazard becomes greater as one moves into the mountains from the lowlands. The erosion hazard is also greater for the northern and southern parts of the lowlands than for the western part. This is slightly contrary to the current extent of erosion in Lesotho. Strömquist et al. (1986) produced a map of the present state of soil erosion in the lowlands based on visual interpretation of Landsat images. They used three erosion classes: slight (I), moderate (II) and severe (III). The most severely eroded areas are the southern and western parts of the lowlands (Fig. 3.8). A comparison between the two maps reveals that large areas of high erosion fall under areas classified as having low erosion hazard. The erosion hazard map shows the effects of factors intrinsic to the system while the erosion map shows the combined effect of intrinsic and extrinsic variables. This was noted in Zimbabwe by Whitlow (1988). The two different maps serve different purposes.

Soil conservation in an organized manner was initiated in Lesotho in 1936 by the British as a result of the Pim Commission (1935). Two types of terraces/bunds were used in the beginning. In the lowlands the bund (or terrace) was made level for 200 m and after this it was made to drop 0.1 % for every 200 m. The top terrace would function as a hill-side ditch, disposing large amounts of water from uphill. In the mountains level grass strips were established with a vertical interval of 1.8 m or less (Wenner, 1982). In the late 40s the terraces in the lowlands were to a great extent replaced by grass strips. By 1954, 80 % of the lowlands was protected by bunds and/or grass strips, all sloping land in the foothills was terraced and buffer grass strips established in the mountains (ibid.). In addition, contour ploughing had been introduced everywhere. Extensive tree planting was also started in 1936, and up to 1972, 40-60 million trees were planted (Powell & Wellings, 1983), but woodlots and natural tree groves covered less than 1 % of the country in 1982 (Potter, 1982). The main objectives were to ensure a supply of fire wood, and to prevent soil erosion. The upper limit for plantation is about 2 500 m, above this elevation tree growth is limited by low temperatures and shallow soils (Berding, 1984b). If proper site preparation is carried out and suitable tree species are selected, rainfall is not a limiting factor in Lesotho (ibid.). Among the trees used are different species of *Pinus*, *Cupressus*, *Populus*, and *Eucalyptus*.

3.2 Field study areas

The locations of the catchments examined in this study are shown in Figure 3.1. They all lie within the Lowland Province. Two of the catchments are situated in the Leribe District, one in the Berea District, one in the Maseru District, two in the Mafeteng District, and two in the Mhales Hoek District. The areas were chosen in pairs with similar climatic conditions. The catchments are represented by the meteorological stations in Leribe, Maseru, Mafeteng and Mhales Hoek (Fig. 3.1). The mean annual air temperature and its variations over the year differ little between the meteorological stations. The station in Maseru serves as an example in Figure 3.9. The mean monthly precipitation and standard deviations for the four stations are shown in Figure 3.10. Some useful facts about the 8 catchments are summarized in Table 3. The slope distribution in the catchments is shown in Table 4 and Figures 3.11 and 3.12. Geological maps of the catchments are shown in Figure 3.13. The catchments have been named after the nearest meteorological station. The local names (nearby village) of the catchments, used in earlier studies, are presented in brackets.

The catchments have previously been studied by Strömquist et al. (1986) who made a comparative study of sheet erosion using air photos and satellite images, and by Nordström (1986a, b) who made a preliminary inventory of gully erosion. In addition Strömquist et al. (1985) studied the extent of sheet and gully erosion, and sediment transfer in the catchment Mhales Hoek 1 (Ha Khitsane). Lundén et al. (1986) studied erosion rates and sediment transfer in the catchments Leribe 1 (Mathokoane 1), Maseru 1 (Sofonia), and Mhales Hoek 1 (Ha Khitsane). Sarr (1986) made a survey of sheet and gully erosion rates in a large area in the southern lowlands in which the catchment Mhales Hoek 1 is included, and Strömquist and Larsson (1988) made a comparative mapping of soil erosion features using colour air photos and SPOT satellite images of the catchments Maseru 1 and 2.

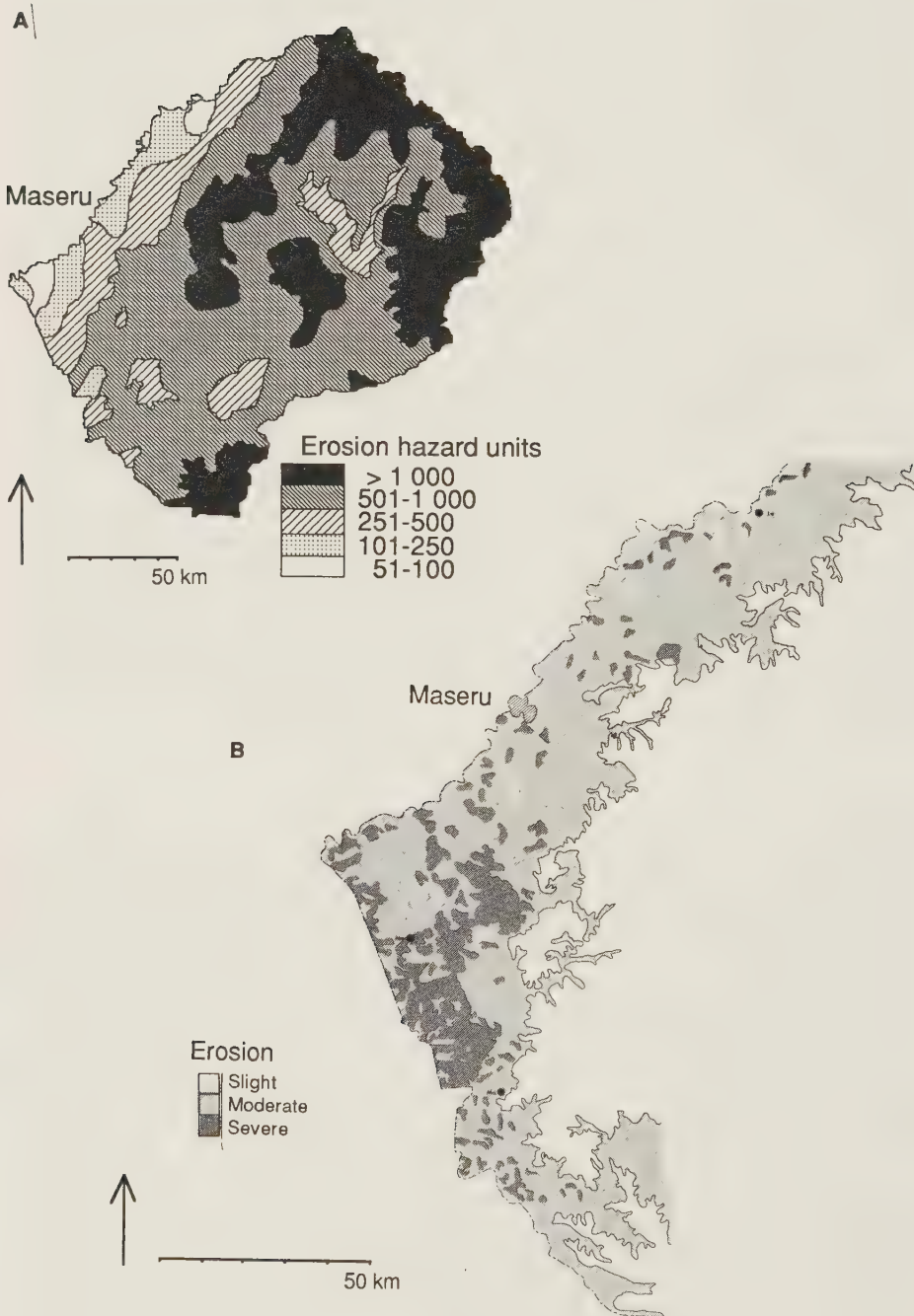


Figure 3.8. A: erosion hazard map of Lesotho. High numbers represent higher erosion hazard (after Chakela, 1987). B: map showing the state of soil erosion in the lowlands of Lesotho in 1983, based on visual interpretation of Landsat MSS images (from Strömquist et al., 1986).

Detailed soil surveys were carried out by Soil Survey Staff in four of the catchments, Leribe 1, Maseru 1, Mafeteng 1, and Mohales Hoek 1. The distribution of different soil units and erodibility classes in these catchments are shown in Figure 3.14 and Table 5. There have not yet been any detailed soil surveys carried out in the southern lowlands (Mohales Hoek). The moisture regime is slightly different from the central and northern lowlands and it has not yet been decided whether the classification and the scientific names should be the same as for the rest of the lowlands. The physical properties of the soils nevertheless resembles the series present in the central and northern lowlands. For convenience, the soil series in the Mohales Hoek 1 catchment were named after the soil series they resemble most.

Five of the catchments have reservoirs built in the late 50s that are now filled with sediment (Leribe 1, Maseru 1 and 2, Mafeteng 1, Mohales Hoek 1). Photos of the catchments are shown in Figures 3.15-3.22.

Leribe 1 (Mathokoane 1)

The topography and geology of the catchment are shown in Figure 3.11, 3.12 and 3.13. The catchment is a broad and gently sloping valley cut in the Burgersdorp formation. The Molteno formation outcrops along the western and eastern boundaries. In the south the Elliot and Clarens formations form a steep escarpment reaching an elevation of almost 2 000 m. Several dolerite dykes cut through the catchment.

A detailed soil survey was carried out in 1987 and the map is shown in Fig 3.14. Forty-nine per cent of the total soil area (91 %) in the catchment is covered with duplex soils, equivalent to 41 % of the total catchment area. Fifty-three per cent of the catchment is used for cultivation. Conservation measures were carried out in the 50s.

A woodlot currently covers 22 ha of the western narrow strip of broken colluvial land between the main gully and the escarpment. Planting was initiated in 1978 and completed in 1981. The species used are mainly *Eucalyptus spp.* and *Acacia spp.* (wattle). Along the main gully in the same area *Populus canescens* was planted. Another woodlot covers 19.5 ha of similar terrain below the escarpment in the north-east. Planting was initiated in 1976 and completed in 1984, using mainly *Eucalyptus spp.*, *Acacia spp.* and *Pinus halepensis*.

Leribe 2 (Mathokoane 2)

The topography and geology of the catchment are shown in Figure 3.11, 3.12 and 3.13. The valley is cut in Elliot and Molteno formations and surrounded by an escarpment formed in Clarens formation. A remnant kopje topped with the more resistant Lesotho formation acts as a divide splitting the valley head in two. Fifty-one per cent of the catchment is used for cultivation. Conservation measures were carried out in the 50s.

Maseru 1 (Sofonia)

The topography and geology of the catchment are shown in Figure 3.11, 3.12 and 3.13. The catchment is situated at the head of a well defined valley cut in the Elliot formation. The Clarens formation outcrops along the valley sides forming a steep sandstone escarpment. Several dolerite dykes and one kimberlite dyke cut through the catchment.

The area was included in the Thaba Bosiu Soil Survey in 1978 and the portion of the map covering the catchment was revised in 1988 and is shown in Figure 3.14. Thirty per cent of the total soil area of the catchment (62 %) are covered by duplex soils, equivalent to 18 % of the total catchment area. Fifty-three per cent of the catchment is used for cultivation. Conservation measures were carried out in the 50s.

A woodlot now covers 32 ha of the western colluvial slope below the escarpment. Planting was initiated in 1977 and completed in 1981, using mainly *Eucalyptus spp.*, *Pinus spp.* and *Populus canescens*.

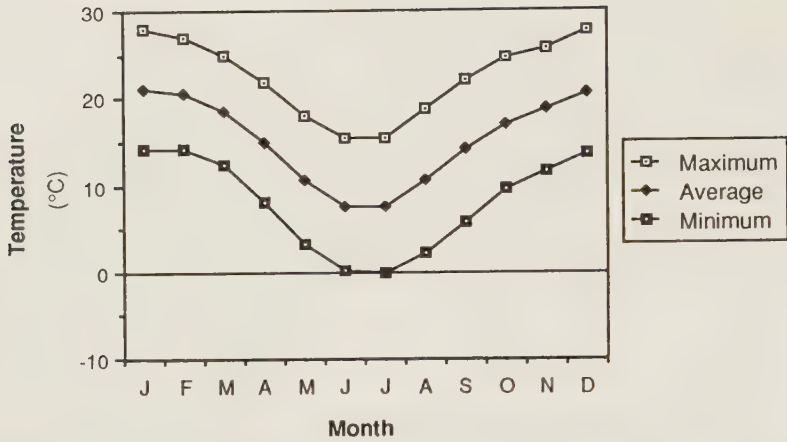


Figure 3.9. Mean monthly temperature and mean monthly minimum and maximum temperatures at the meteorological station in Maseru (source: FAO, 1984).

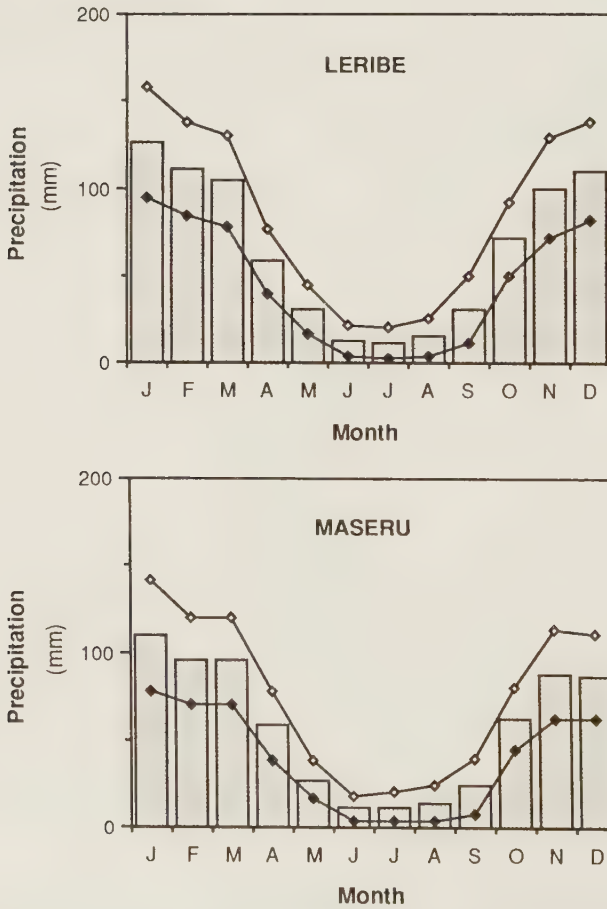


Figure 3.10. Mean monthly rainfall and standard deviation at the four meteorological stations in Leribe, Maseru, Mafeteng and Mochales Hoek (based on data from Hydrol. Surv., 1970, 1988).

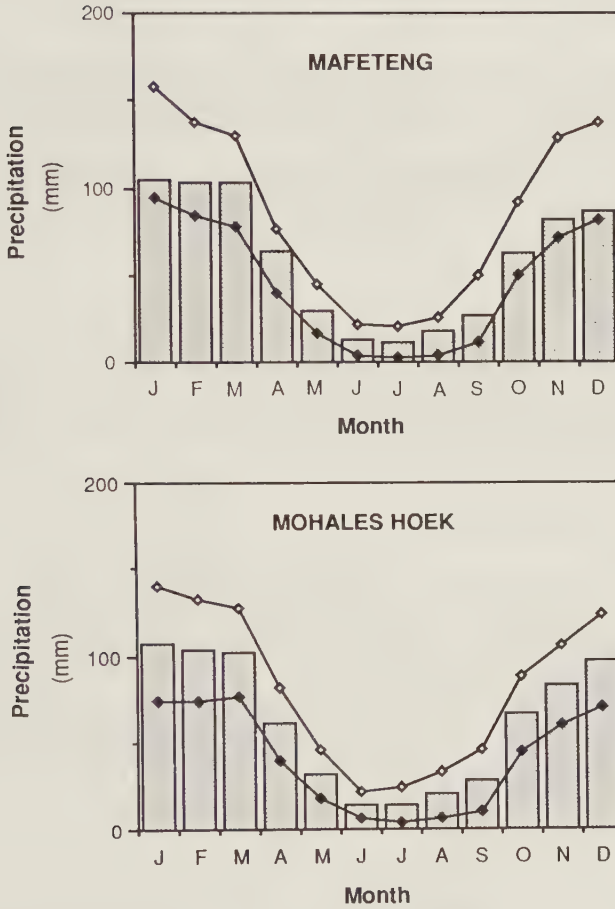


Figure 3.10. Continued.

Maseru 2 (Marabeng)

The topography and geology of the catchment are shown in Figure 3.11, 3.12 and 3.13. The catchment is situated in a valley cut in the Elliot formation surrounded by smoothly rounded hilltops of the Clarens formation. The north-eastern boundary consists of a steep escarpment. The other valley sides are relatively gently sloping, in the south reaching up onto the Berea Plateau. Several dolerite dykes cut through the catchment. Thirty-six per cent of the catchment is used for cultivation. Conservation measures were carried out in the 50s.

Mafeteng 1 (Matsoseng)

The topography and geology of the catchment are shown in Figure 3.11, 3.12 and 3.13. The catchment is situated on a gently undulating pediplain on the Burgersdorp formation. The Molteno formation forms an escarpment in the south-east. Several dolerite intrusions are found in the catchment.

A detailed soil survey was carried out in 1988 and the map is shown in Figure 3.14. Duplex soils cover 75 % of the soil area of the catchment (92 %), equivalent to 69 % of the catchment area. Seventy-five per cent of the catchment is used for cultivation. Conservation measures were carried out in the 50s.

Mafeteng 2 (Boleka)

The topography and geology of the catchment are shown in Figure 3.11, 3.12 and 3.13. The catchment is part of a gently sloping valley cut in Molteno and Elliot formations with an escarpment in the west formed in the Clarens formation. Three dolerite dykes cut through the catchment. Fifty-six per cent of the catchment are used for cultivation. Conservation measures were carried out in the 50s.

Mohales Hoek 1 (Ha Khitsane)

The topography and geology of the catchment are shown in Figure 3.11, 3.12 and 3.13. The catchment is situated on a pediplain on the Molteno formation with the Elliot formation forming hills with escarpments. At the highest point in the west, the Clarens formation outcrops forming a second escarpment. A dolerite intrusion caps the highest point in the north. Three dolerite dykes cut through the catchment.

A detailed soil survey was carried out in 1987 and the map is shown in Figure 3.14. Duplex soils cover 70 % of the area covered by soil in the catchment (75 %), equivalent to 52 % of the catchment area. Fifty-two per cent of the catchment is used for cultivation. Conservation measures were carried out prior to 1950.

Mohales Hoek 2 (Maphutseng)

The topography and geology of the catchment are shown in Figure 3.11, 3.12 and 3.13. The catchment is a broad and gently sloping valley cut in the Molteno formation surrounded by escarpments formed in the Elliot formation. In the south-east a remnant of the Clarens formation forms a peak of 1850 m. Two dolerite dykes cut through the catchment. Fifty-six per cent of the catchment is used for cultivation. Conservation measures were carried out before 1950.

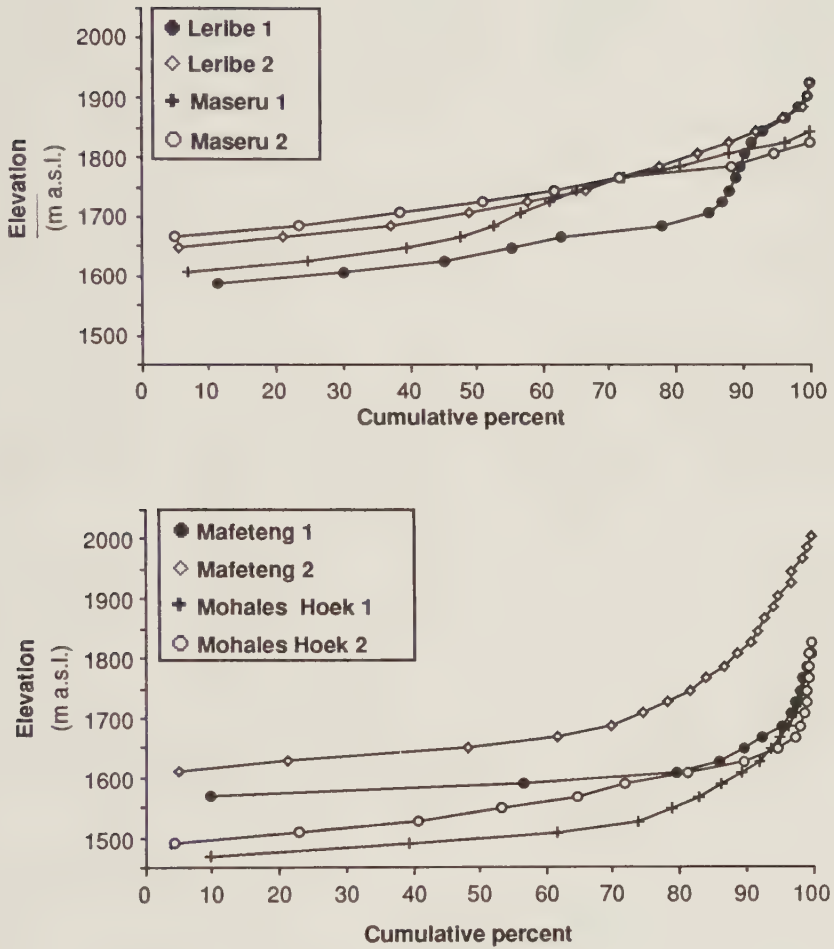


Figure 3.11. Hypsographic curves of the study catchments.

Table 3. Comparison between the eight catchments used in the study.

	Leribe		Maseru	
	1	2	1	2
Location	28°57'S 28°03'E	28°58'S 28°05'E	29°19'S 27°37'E	29°16'S 27°38'E
Local name	Mathokoane 1	Mathokoane 2	Sofonia	Marabeng
District	Leribe	Leribe	Maseru	Berea
Meteorological station	Leribe	Leribe	Maseru	Maseru
Size (km ²)	10.2	5.7	6.0	2.5
Average elevation (m)	1670	1741	1710	1743
Mean annual precipitation (mm)	785	785	684	684
Number of days/year P> 1 mm (1)	72	72	70	70
Number of days/year P> 10 mm (1)	27	27	22	22
Number of days/year P> 25 mm (1)	7	7	6	6
Mean annual temperature (° C) (1)	14.5	14.5	15.3	15.3
Mean annual evaporation (Class A pan)(mm) (1)	2000	2000	2130	2130
Mean annual relative humidity (%) (1)	61	61	57	57
Geological formations	Burgersdorp Molteno Elliot Clarens	Molteno Elliot Clarens Lesotho	Elliot Clarens Lesotho	Elliot Clarens
Cultivated area (%)	53	51	53	36
Grazing area and marginal lands (%)	35	44	42	59
Settlement area (%)	12	5	5	5
Woodlot (%)	4	0	5	0

(1) Binnie and Partners, 1972a.

Table 3. Continued.

	Mafeteng		Mohales Hoek	
	1	2	1	2
Location	29°40'S 27°16'E	29°42'S 27°23'E	30°05'S 27°05'E	30°14'S 27°27'E
Local name	Matsoseng	Boleka	Ha Khitsane	Maphutseng
District	Mafeteng	Mafeteng	Mohales Hoek	Mohales Hoek
Meteorological station	Mafeteng	Mafeteng	Mohales Hoek	Mohales Hoek
Size (km ²)	5.0	4.1	6.2	6.1
Average elevation (m)	1609	1693	1532	1563
Mean annual precipitation (mm)	705	705	727	727
Number of days/year P > 1 mm	54	54	69	69
Number of days/year P > 10 mm	24	24	26	26
Number of days/year P > 25 mm	0	0	9	9
Mean annual temperature (° C) (1)	14.9	14.9	16.0	16.0
Mean annual evaporation (Class A pan)(mm)(1)	2080	2080	2080	2080
Mean annual relative humidity (%) (1)	53	53	49	49
Geological formations	Burgersdorp Molteno	Molteno Elliot Clarens	Molteno Elliot Clarens	Molteno Elliot Clarens
Cultivated area (%)	75	56	52	56
Grazing area and marginal lands (%)	18	40	44	31
Settlement area (%)	7	4	4	13
Woodlot (%)	0	0	0	0

Table 4. Slope distribution in the eight study catchments.

	Leribe		Maseru		Mafeteng		Mohales Hoek	
	1	2	1	2	1	2	1	2
Slope class (% of catchment area):								
1: 0-5 %	18	9	12	12	51	11	23	13
2: 6-10 %	22	12	27	18	20	19	22	22
3: 11-20 %	33	27	25	27	14	36	26	36
4: 21-40 %	21	31	20	30	10	17	16	24
5: > 40 %	6	21	16	13	5	17	13	5
Average slope (%) (1)	15	24	20	20	10	23	16	16

(1) Average slope calculated from actual slope in %, not slope class.

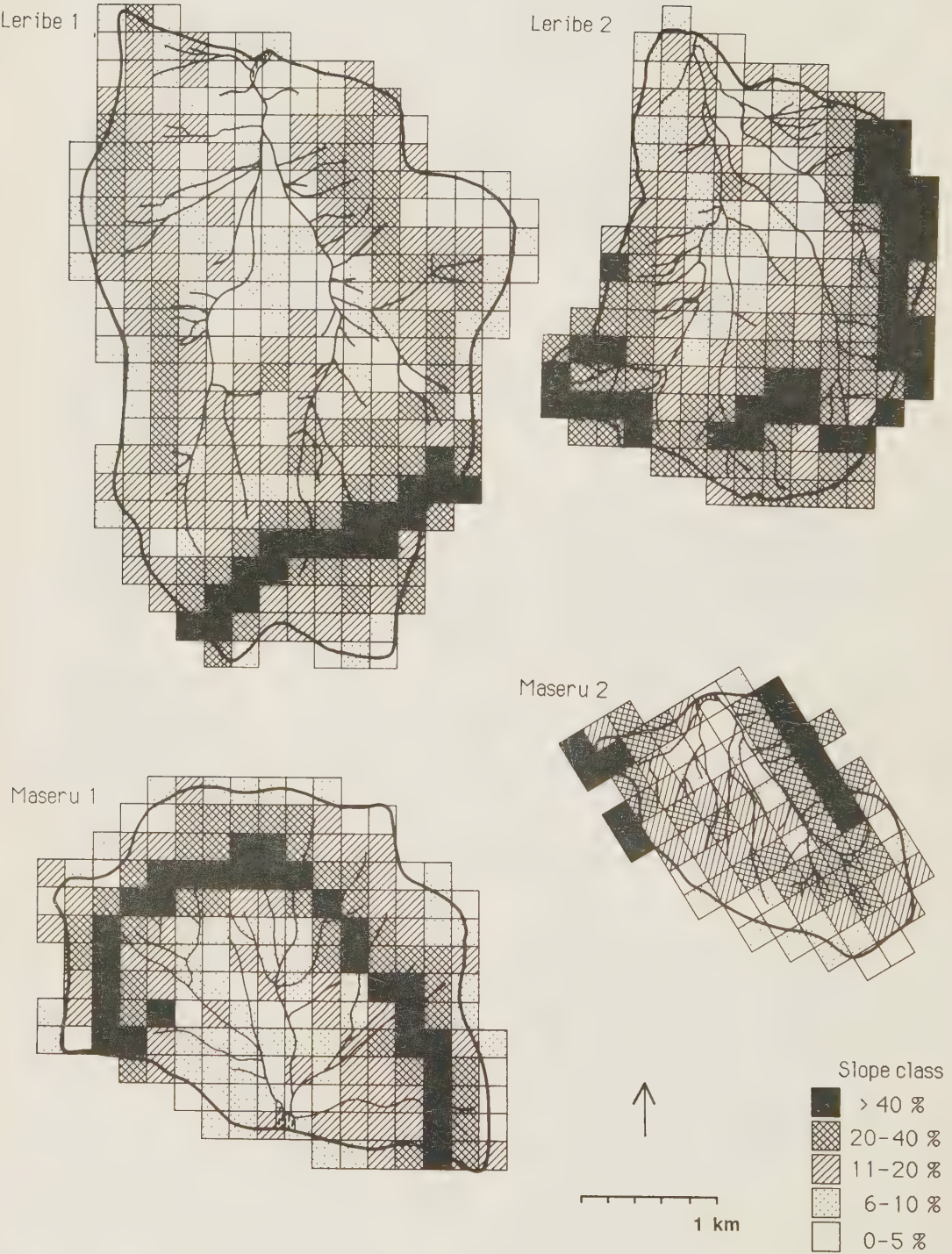
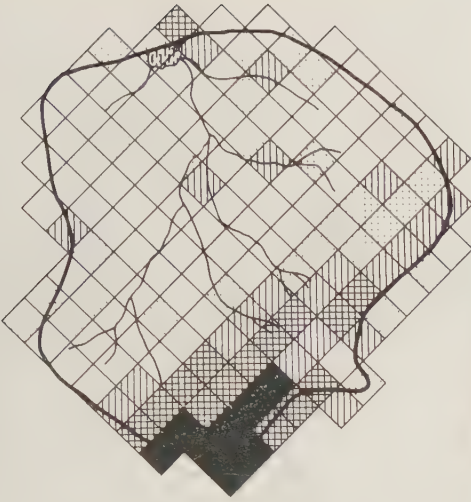
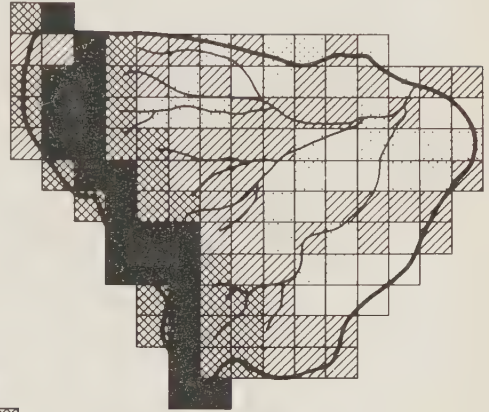


Figure 3.12. Slope distribution in the study catchments.

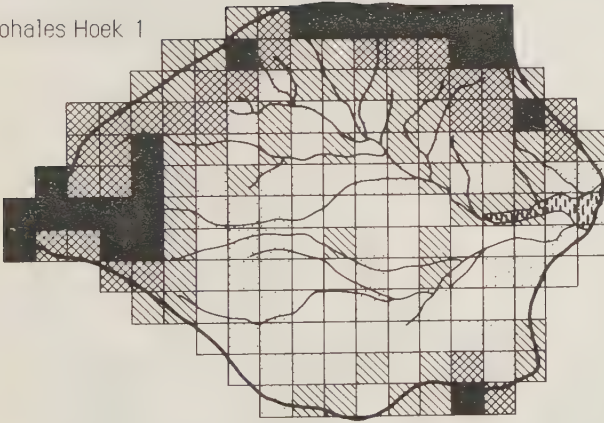
Mafeteng 1



Mafeteng 2



Mohaies Hoek 1



Mohaies Hoek 2

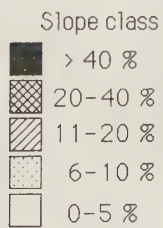
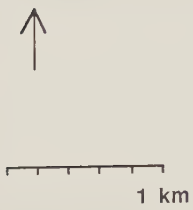
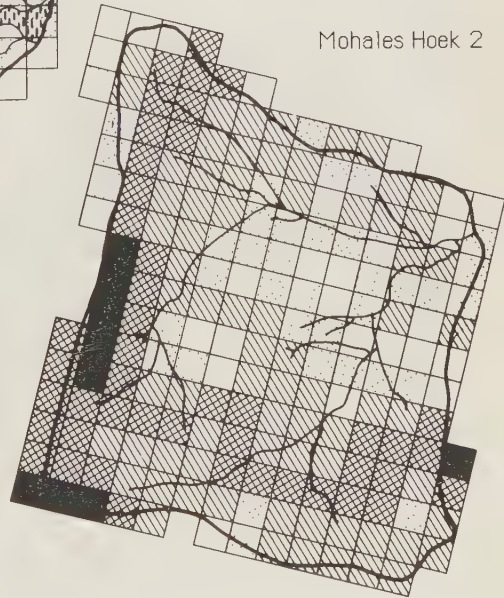


Figure 3.12. Continued.

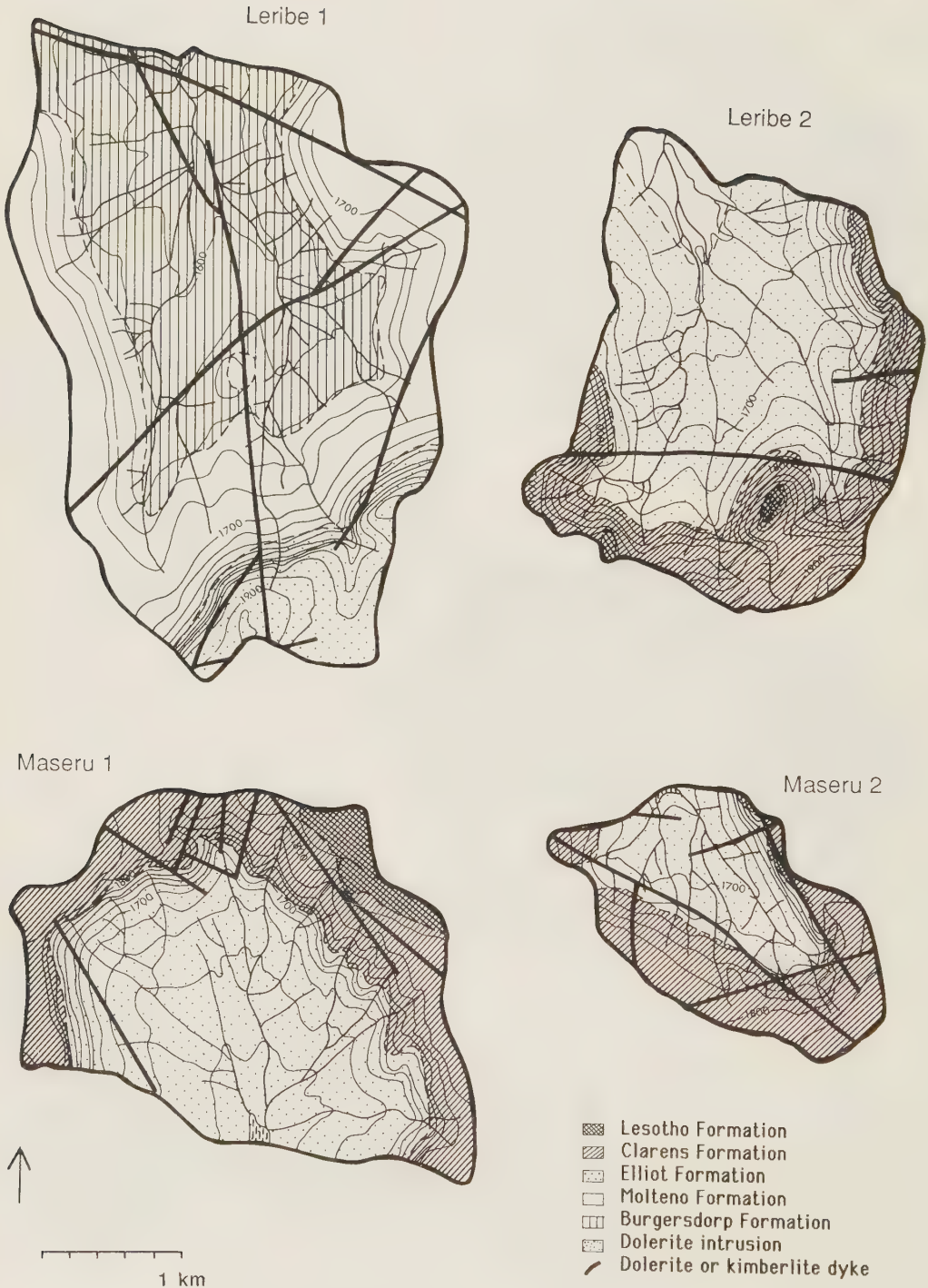
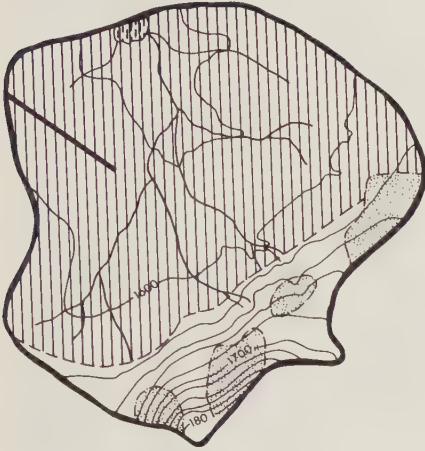


Figure 3.13. Geological maps of the study catchments (after: Directorate of Overseas Survey, 1981, 1982).

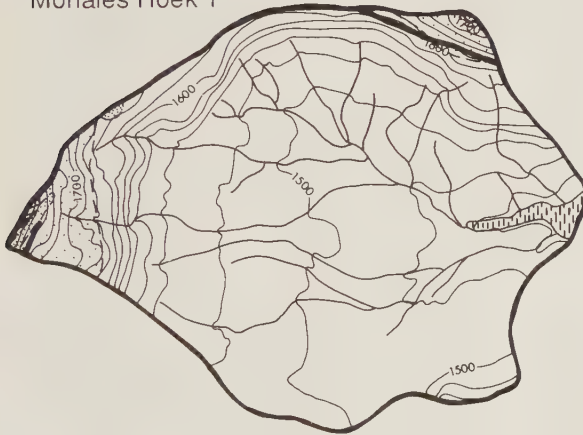
Mafeteng 1



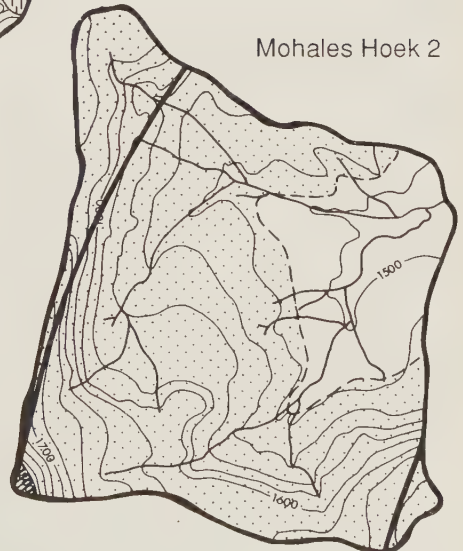
Mafeteng 2



Mohales Hoek 1



Mohales Hoek 2



-  Lesotho Formation
-  Clarens Formation
-  Elliot Formation
-  Molteno Formation
-  Burgersdorp Formation
-  Dolerite intrusion
-  Dolerite or kimberlite dyke



1 km

Figure 3.13. Continued.

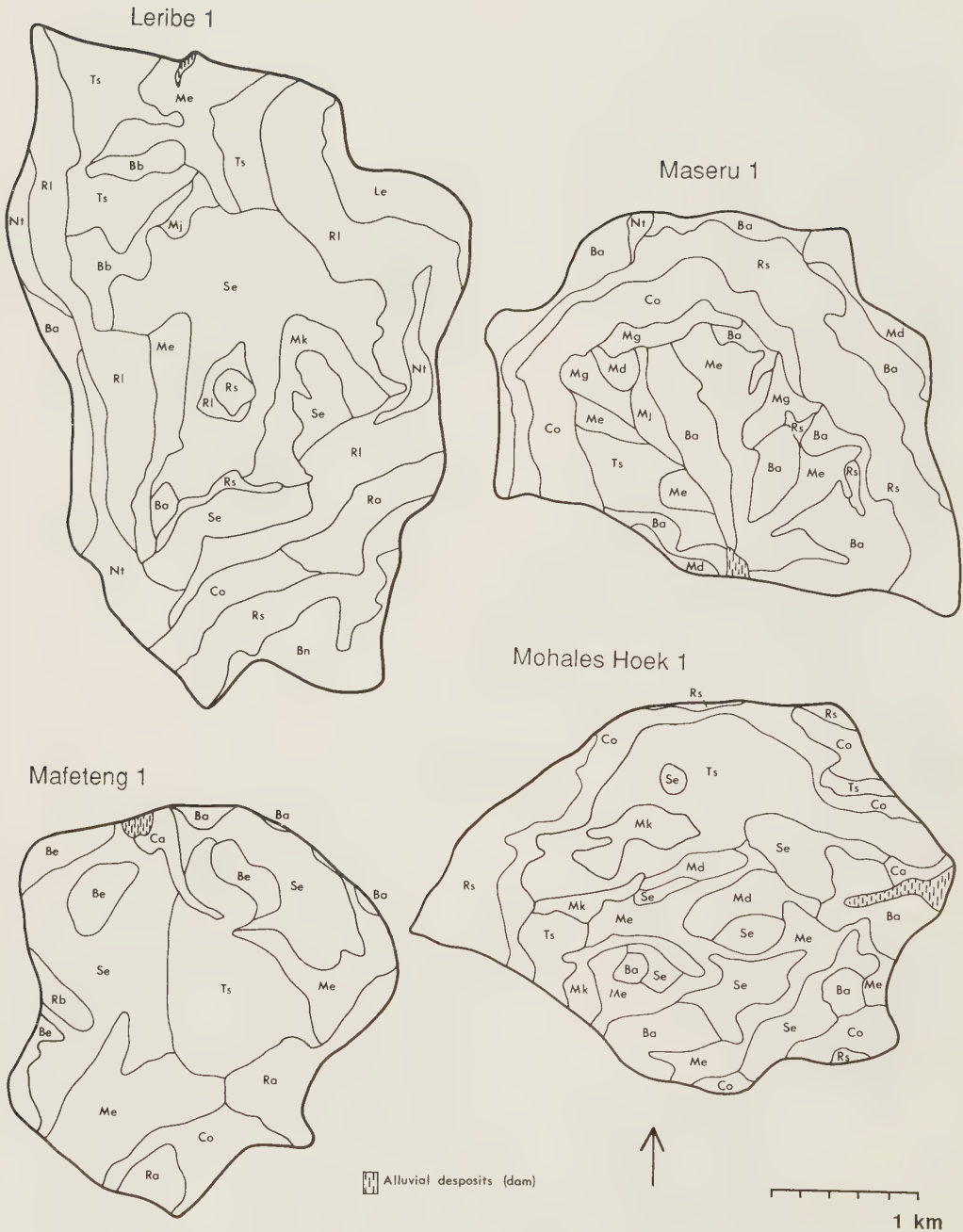


Figure 3.14. Soil maps of the catchments Leribe 1, Maseru 1, Mafeteng 1 and Mohales Hoek 1. The map symbols equal the following soil units: Ca=Caledon, Mj=Majara, Nt=Ntsi, Ba=Berea loam, Bb=Berea fine sandy loam, Md=Matela, Se=Sephula, Me=Maseru, Ts=Tsiki, Le=Leribe, Ra=Ralebese, Mg=Malele, Be=Bela, Mk=Maseru dark variant, Rl=Rough broken land, Co=Colluvial land, Rs=Rockland (sandstone), and Rb=Rockland (basalt). Sephula, Maseru and Tsiki are duplex soils. For detailed information on the properties and characteristics of the soil units see Appendix 1.

Table 5. Distribution of different soil units and erodibility classes in the four catchments where soil surveys were carried out. The map symbols are presented in brackets. For a detailed description of the different soil units and their properties see Appendix 1. Tsiki, Sephula and Maseru soils are duplex.

	Leribe 1	Maseru 1	Mafeteng 1	Mohales Hoek 1
Total area covered by soil (%)	91	62	92	75
Area covered by duplex soils (%)	41	18	69	52
Area covered by duplex soils as % of soil area	49	30	75	70
Soil unit:				
Caledon (Ca)	0	0	2	2
Majara (Mj)	1	2	0	0
Ntsi (Nt)	6	1	0	0
Berea-Ntsi (Bn)	4	0	0	0
Berea (Ba)	3	31	1	10
Berea (Bb)	3	0	0	0
Matela (Md)	0	5	0	5
Sephula (Se)	21	0	32	15
Maseru (Me)	7	13	19	13
Tsiki (Ts)	9	5	18	24
Leribe (Le)	4	0	0	0
Ralebese (Ra)	3	0	10	0
Maliele (Mg)	0	6	0	0
Bela (Be)	0	0	10	0
Maseru dark (Mk)	4	0	0	7
Rough broken land (Rl)	25	0	0	0
Colluvium (Co)	3	13	6	14
Rockland (basalt) (Rb)	0	0	2	0
Rockland (sandstone) (Rs)	7	24	0	10
Soil erodibility class (as % of catchment area)(1):				
k < 0.25	0	6	2	2
k 0.25-0.50	74	36	53	36
k > 0.50	17	20	37	38

(1) The sum does not add up to 100 % but to the percentage of the catchment area covered by soil.



Figure 3.15. View of the catchment Leribe 1 towards the north (May 29, 1985).



Figure 3.16. View of the catchment Leribe 2 towards the north (May 30, 1985).

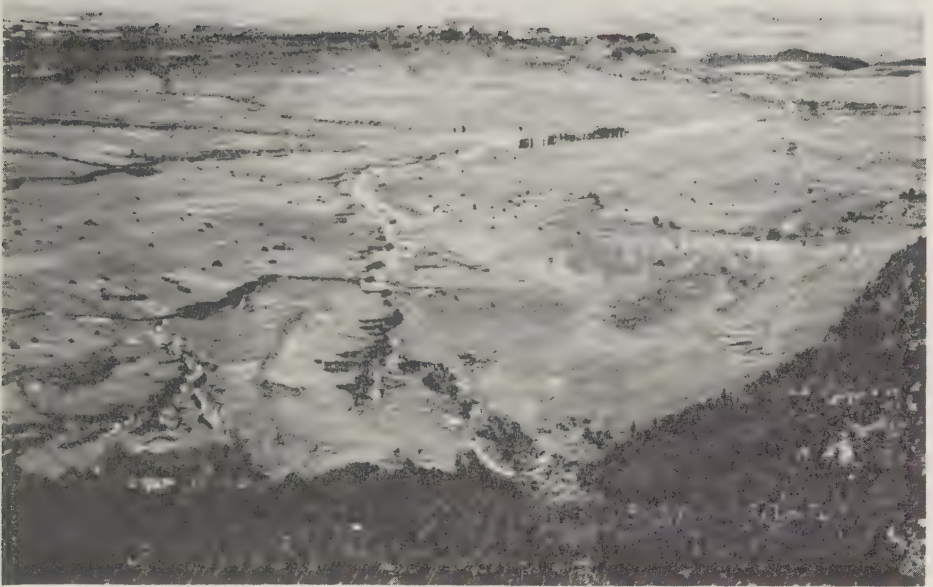


Figure 3.17. View of the catchment Maseru 1 towards the south. The dam is situated at the row of trees in the centre of the photo (March 14, 1988).



Figure 3.18. View of the catchment Maseru 2 towards the north (May 25, 1985).



Figure 3.19. View of the catchment Mafeteng 1 towards the north, just after a heavy rain. The dam is situated at the row of trees in the centre of the photo (Jan. 25, 1985).



Figure 3.20. View of the catchment Mafeteng 2 towards the east (March 20, 1988).



Figure 3.21. View of the catchment Mohales Hoek 1 towards the east (April 1, 1988).



Figure 3.22. View of the catchment Mohales Hoek 2 towards the east (May 26, 1985).

3.3 Methodology

The methodology is presented in three sections: 3.3.1 which deals with the methodology used in the field and for the inventory of gullies and related processes and variables; 3.3.2 which discusses the methods used for data processing and statistical analyses; and 3.3.3 which describes the methods used for analysing rainfall variation and trends for the four meteorological stations. Table 6 provides a comparative list of which surveys, inventories and calculations were conducted in the different catchments.

Table 6. List of the surveys and inventories carried out in the different catchments.

	Leribe		Maseru		Mafeteng		Mohaies Hoek	
	1	2	1	2	1	2	1	2
Gully area, length and heads:								
1950	x	x	x	x	x	x	x	x
1961/62	x	x	x	x	x	x	x	x
1979/80	x	x	x	x	x	x	x	x
Landuse 1979/80	x	x	x	x	x	x	x	x
Soil survey	x		x		x		x	
Field inventory	x	x	x	x	x	x	x	x
Grid square slope map	x	x	x	x	x	x	x	x
Grid square statistical analyses	x		x		x		x	
SARCCUS sheet erosion	x	x	x	x	x	x	x	x
SARCCUS gully erosion	x	x	x	x	x	x	x	x

3.3.1 Field methodology and gully inventory techniques

Lesotho has a good coverage of aerial photographs. Panchromatic photographs covering the whole country are available from 1950, 1961/62 and 1979/80. In addition colour photographs are available from 1983.

A detailed inventory of the gullies in the catchments was carried out using the photographs from 1950, 1961 or 1962 (Mohaies Hoek 2), and 1979 (Mafeteng 1 and 2, Mohaies Hoek 2) or 1980. All photos were taken in April/May except the ones from 1979 which were taken in August/September. The 1979/80 photos were also used for determining the areas under different landuse in the catchments. The colour photographs were tested for the inventory of gullies, but they are enlargements and their resolution is not as good as for the panchromatic photographs. It proved to be unsatisfactory for detailed delineation of gullies. The method of using air photos from different years for comparative gully erosion studies has previously been employed by, for example, Rapp et al. (1972) and Chakela (1981).

The scales of the air photos used differ depending on the flight altitude and the elevation of the area in question. The scale was determined for each photo by comparing a distance known from the topographic map (1:20 000) with the same stretch in the air photo. The scales range from 1:25 000 to 1:30 000 except for the 1962 photos which have a scale of roughly 1:38 000. This was considered too large a discrepancy and the photos were enlarged bringing the scale to just over 1:29 000, a scale similar to that of the 1961 photographs.

When the gullies had been delineated and marked on a transparency covering the air photograph, the gully lengths and areas were measured, the former using a digitizer (Altek ACT 46-2). The digitizer provides three decimals and the error of the apparatus is negligible compared to that of the user during the measuring procedure. The latter increases as the scale decreases (e.g. from 1:20 000 to 1:50 000) and at a scale of 1:20 000 it was determined to be about 1 %.

The gully areas were measured using an area meter developed and described by Ekman and Wastensson (1968). It is a photoelectric method whereby a photocell detects black areas on a white surface. The transparency is placed on a rotating drum. As the drum rotates the

photocell also moves at a slow speed along the drum and hence detects and records the black areas in two dimensions. The maximum error of the apparatus is estimated to 4 % (ibid.). Again, the error is negligible compared to that of the interpreter. The delineation of the gullies in the air photos is subjective but the error is presumably consistent, i.e. it does not affect the final results when comparing the gully development in the catchments.

The inventory made it possible to study the degree (severity) of gully erosion in the catchments, and the development, i.e. increase in area (expansion) and drainage density (extension), during the periods 1950-1961/62 and 1961/62-1979/80. Expansion may have taken place through regular side wall processes, or through the fusion (sideways) of several small gully heads along the gully walls. The latter is often the case where piping is present, creating more or less extensive badlands. The two measures, expansion and extension, are related in such a way that an increase in drainage density also, to a certain extent, will affect the gully area. It was also possible to calculate the annual rates of development as a mean of 11-12 and 17-20 years respectively, i.e. extension rates as $\text{m}/\text{km}^2/\text{year}$ and expansion rates as $\text{m}^2/\text{km}^2/\text{year}$. In addition to the inventory of gully length and area in each catchment, the number of gully heads in the different years was counted and the development rate (new heads/ km^2/year) calculated. The portion of gully heads at discontinuous gullies was also determined. An extension/expansion ratio was calculated for each of the two periods, 1950-61/61 and 1961/62-79/80, and for the whole period 1950-1979/80. This can be seen as a measure of which of the gully development processes, extension or expansion, dominated in the catchments during each period.

One might question whether the values of drainage density and gully area for the catchments Mohales Hoek 2, Mafeteng 1 and 2 should be adjusted to the years 1961 and 1980 instead of using the values as they are for 1962 and 1979. There are two options:

1. The values are adjusted by subtracting or adding the equivalent of one year's expansion and extension.
2. The values are left as they are and compared with the other catchments with the knowledge that the gullies have developed one year longer or shorter respectively.

Both options have advantages and disadvantages. The first option assumes that the gully development (rate) is constant and can be extrapolated. The second option compares the catchments when the gullies have developed one year further in one area (1962) and one year less in three areas (1979). It is not possible to exactly determine the development in one single year during the periods 1950-61/62 or 1961/62-79/80, only the total gully growth can be established with certainty. It was therefore considered too great an assumption to adjust the values of gully area and drainage density based on average growth rates and hence the second option has been adopted. Extension and expansion rates, and gully head development rate were, however, calculated for the time periods concerned for each separate catchment.

A detailed field survey of gully related parameters was carried out in the catchments in January to June 1985, April 1987 and April 1988. During the survey an inventory was made along all the gullies and at every well developed gully head. The latter has been distinguished from tributary gully initiation along stretches where gully erosion processes are present, but no clearly defined headcut has developed yet, e.g. piping is visible as numerous pipe inlets or outlets but the former have not yet fused to form a continuous gully. It should be noted that the definition of a "well developed" gully head as opposed to the contrary is not a difference in scale as a small gully head may very well be well developed.

During the field inventory the following was noted along every gully:

- occurrence of piping
- cross-section at relevant locations
- approximate depth at the cross-section
- if the gully had cut down to resistant bedrock

The following was noted at every gully head:

- headcutting with presence of piping
- if the gully head had extended to resistant bedrock (i.e. reached its ultimate extension)
- if the gully had cut down to resistant bedrock

- slope above the gully head
- cross-section about 5 m downstream from the head
- approximate depth at cross-section
- if the gully head was found in connection with a terrace, cultivation or road/path

Piping is very often hard to discover in the field due for example to debris covering the outlet or vegetation hiding the inlet. In order for a gully stretch to qualify as having piping, the process had to be clearly detectable, i.e. showing a visible outlet or inlet. The inventory of piping therefore shows the minimum extent. Furthermore, in an area where piping is present and a gully head has developed, piping is not the sole cause of further extension. Surface runoff aids in the headcutting process. It can thus be assumed that surface runoff is a gully eroding agent, more or less dominating, at all well developed heads whether piping is present or not.

The length of gully stretches that were determined as having piping was measured. Piping is not necessarily present on both sides of a gully at the same location and hence both sides of the gullies were treated as potential piping sites. The maximum length of piped stretches in a catchment is therefore twice the total gully length. Based on this a piping index was introduced as:

$$I(p) = \frac{\text{total length of piping stretches}}{\text{total length of gullies} \times 2}$$

The maximum value is 1, achieved when piping is present along both sides of all gullies in the catchment.

The cross-section and material in the bottom were determined, and the depth was estimated at relevant locations along all gullies. The intervals ranged from 20 to 300 m depending on the nature of the gully and if sudden changes occurred. The same parameters were recorded at all gully heads about 5 m downstream from the headcut. The cross-sections recorded were the ones presented in Figure 2.2 and explained in Section 2.3 of this paper.

At the gully heads it was noted whether they were found in direct connection with cultivation, a terrace or road/path, and if these factors were the direct cause or contributing significantly to the headward extension. Cultivation and roads/paths are easier to distinguish as having initiated gully erosion, than are terraces. Sometimes the relationship is clear, i.e. the gully has been initiated by either of the factors. In other cases the gully head is found in conjunction with one of the factors but it is impossible to determine whether the factor was the actual initiator of the headcut. It may nevertheless assist and perhaps accelerate the development of the gully. The gully may have started further downslope and extended, eventually reaching a terrace or road/path where the runoff is concentrated and erosion accelerated. Similarly, a gully that has extended past the terraces and cultivated fields may have a head which at present is not found in connection with any of the three factors. However, the gully may have originated at a terrace for example.

The volume of sediment eroded by gullies was calculated for all catchments by multiplying the average depth estimated in the field and the gully area measured. This figure is very rough since gully outline and cross-section may vary within the catchments. It nevertheless gives an indication and comparison between the catchments.

3.3.2 Data processing and analysis

For further analysis the catchments were subdivided into grid squares 200 by 200 m in size (0.04 km²) equivalent to one cm² on the topographic map (1:20 000). The method of using grid squares for surveying processes like erosion has been used on a smaller scale by, for example, Strömquist et al. (1986) and Strömquist and Larsson (1988), who used the same size of grid squares (200 x 200 m) to map erosion in Lesotho, and by Giordano (1984) who used 0.25 km² grid squares to map vegetation, soils etc in Morocco. Whitlow (1985) and Chakela (1987) used the method on a large-scale regional/national level in Zimbabwe and Lesotho respectively. It is a systematic and simple, although sometimes quite laboursome, method of monitoring different parameters in an area. This investigation deals with 8 catchments, a figure far from satisfactory for statistical analyses when using catchment

parameters. The grid square method therefore provided a larger and statistically useful database.

A method proposed by Wentworth (1930) and adapted to the metric system by Stocking (1972) was used to produce slope maps of all 8 catchments (Fig. 3.11). The slope maps are based on the topographic maps (1:20 000). A grid overlay was used and diagonals drawn across the squares. The total length of the diagonals in each square was 0.56 km. The number of contours crossed by the diagonals were counted and then the slope calculated according to the formula (ibid.):

$$\text{Slope in degrees} = \tan^{-1} \left(\frac{\text{contour interval} \times \text{number of contour crossings/km}}{636.6} \right)$$

In this particular case, where the contour interval is 10 m and the total length of the diagonals is 0.56 km, the formula will be (converted to slope in %):

$$\text{Slope in \%} = \frac{45}{100} \tan^{-1} \left(\frac{\text{number of contour crossings}}{35.6496} \right)$$

Slope length is another an important morphological factor in connection with soil erosion. In a terraced area the length is reduced to the distance between the terraces, at least as long as the terraces are well maintained. A break in a terrace not only increases the slope length to the field downslope but also collects and concentrates the runoff increasing the erosivity. In addition, gullies do not always follow natural drainage lines. They cut across the fields seemingly at random, sometimes almost following the contours, sometimes draining straight down the slope. Variations in microtopography further complicates any attempt to measure slope length on a detailed basis. The grid square method was tested but the accuracy of the measurements was found unsatisfactory and the method abandoned. As the terrace spacing, i.e. slope length, is dependent on the slope angle, the latter will serve as the sole slope factor.

Strömquist et al. (1986) introduced the method of grid squares for mapping erosion according to the SARCCUS classification system. This method was adapted in the present study. Both sheet and gully erosion were determined using the 5 classes proposed by the SARCCUS method (Anon., 1981): 1. No apparent erosion; 2. Slight erosion (noticeable); 3. Moderate erosion (clearly noticeable but less than 25 % of the square affected); 4. Severe erosion (25-50 % of the square affected); 5. Very severe erosion (more than 50 % of the square affected).

Grid overlays were produced to fit the different air photo scales and then the severity of sheet and gully erosion was determined for every square. Due to the difference in scale of the air photos over the years, it is not possible to get a perfectly fitting grid square from year to year, i.e. get the same grid square to cover exactly the same 4 ha all three years. It is not feasible, therefore, to compare the erosion development in each square separately from 1950. This is particularly so for gully erosion, since a slight shift in the position of the grid square may bring it to cover part of another gully, rendering the square an entirely different erosion class. Instead, the grid squares were used to calculate the average erosion class for the catchments and the development through the years for the catchment as a whole.

Some inventories to be used in statistical analyses, were made only in the 1979/80 air photographs, again using the grid square method. The inventories were carried out in the four catchments for which soil maps are available and for each grid square include: gully length, number of heads and landuse. It was not considered practicable to measure the gully area in each grid square, the SARCCUS classification serves roughly the same purpose. In addition several other parameters were determined using the results from the field inventory and from the soil maps, see Table 7. For some of the parameters actual figures were used, for others class limits were determined. The latter are explained in detail in Appendix 2. The erodibility in each grid square was determined using k-values provided by Scherer (1978) and Conservation Division (1979a). The k-value as an index of erodibility was introduced in the USLE equation by Wisnmeier and Smith (1978) and takes soil texture and structure, organic matter content, and permeability into consideration.

Most of the data assembled in the four catchments were calculated as values per km² or as averages for the catchment as a whole. The data retrieved by the grid square method in the 4 main catchments (Leribe 1, Maseru 1, Mafeteng 1, Mhales Hoek 1) was analysed statistically.

Each grid square in the catchments was assigned a value for every parameter. The catchments were analysed separately and together. The parameters were compared statistically using Spearman's ranking correlation coefficient, which is a non-parametric test that can be applied to statistics recorded on the nominal or ordinal scale (e.g. classified data) (Till, 1974). It provides a measure of the correlation between rankings of two different variables. The values of each variable are ranked from high to low. The rankings are then compared and if they tend to increase together, the variables are positively correlated, if the rankings increase and decrease respectively, the correlation is negative. The value is always between -1 and +1, the closer the value is to ± 1 , the better the correlation (positive or negative). Hence, if the correlation coefficient is 0 there is a total absence of correlation between the two variables (McClave & Dietrich, 1982). The formula is provided in Appendix 3.

Table 7. Parameters determined using the grid square method of statistical analyses for four of the catchments (Leribe 1, Maseru 1, Mafeteng 1, Mhales Hoek 1). For class limits see Appendix 2.

Parameter	measure/classes
Gully length	meters
Gully heads	number
Gully depth	1-3
Presence of piping	1-3
SARCCUS gully erosion classification	1-5
SARCCUS sheet erosion classification	1-5
Slope	%
Duplex soils	1-5
Soil erodibility	1-5
Landuse	1-5

3.3.3 Rainfall analysis

The meteorological stations used in this study are Leribe, Maseru, Mafeteng and Mhales Hoek. The rainfall data was compared and analysed for each of the four stations to see if any trends or differences could be detected and then used when comparing the erosion development between the 8 catchments.

The meteorological stations in Leribe and Mafeteng have the longest monthly rainfall records of the four stations, ranging back to October 1886 and January 1887 respectively. For the Leribe station data are lacking for the period July 1901 through May 1905, and only sporadic monthly values are available for the period May 1975 through April 1980. Values are also missing for September and December 1981 and for May 1983. This makes the annual rainfall curve discontinuous, especially in the seventies. For the Mafeteng station values are missing for the period January 1911 through September 1920; for March through June 1972; September and December 1980; August 1981; March, April, June, and October 1986; and February 1987. The rainfall record for Maseru is continuous from January 1921 through September 1985 when the station was moved. Mhales Hoek has a continuous record from January 1896 through November 1973. Data are missing for December 1973; February, July and August 1976; January and February 1980; September 1981; and August 1983.

In order to make the rainfall analyses comparable between the different meteorological stations, rainfall data from January 1921 to December 1987 were used. The mean annual and monthly precipitation, standard deviation and coefficient of variance were calculated based on available annual/monthly values during this period. The coefficient of variation is defined as the standard deviation in per cent of the mean rainfall (McClave & Dietrich, 1982). Normally

mean rainfall figures are based on the latest 30 years of records but since the rainfall was to be used in analyses and compared for a longer period than 30 years, mean monthly and annual rainfall at the different stations was calculated using all available records since 1921.

In an analysis of rainfall conditions the factor of antecedent rainfall has to be considered. A prolonged drought will lead to a deterioration of the vegetation cover, and a following wet spell may cause severe erosion, an effect that applies to annual as well as monthly rainfall. An analysis solely of annual rainfall is in this case too rough as a year that appears to be "normal" very well may have extremes during the separate months. The analysis of antecedent rainfall conditions was basically a detailed search in the rainfall records for dry-wet sequels that may have been potentially erosive, i.e. a period of low rainfall (annually or monthly) followed by a period of high rainfall. The analysis was carried out for the four meteorological stations for the period 1950 to 1980, which is the period during which gully erosion was analysed. It is, of course, impossible to determine whether or not erosion occurred, during these individual sequels, and to what extent. The analysis is only speculative, and indicates when the conditions for soil erosion were favourable, as far as rainfall is concerned.

The annual and monthly rainfall figures were compared with the mean and the deviations calculated and plotted. To detect possible trends in the rainfall, ten year running means of the annual and monthly rainfall were calculated and the slope of the regression line determined for annual rainfall and for every month.

4 RESULTS

4.1 Air photo interpretation, gully length and area measurements

The distribution of gullies in the catchments for 1950, 1961/62 and 1979/80, and the extent of piping are shown in Figures 4.1 through 4.8. The results of the air photo interpretation and gully length, area and head measurements and calculations are shown in Table 8. For convenience the results are summarized in Table 9 where the catchments having the highest, second highest and lowest value for each parameter are shown.

Drainage density and gully extension

Figure 4.9 shows the drainage density in 1950, 1961/62 and 1979/80, and the extension rate, i.e. increase in gully length per year, during the periods 1950-1961/62 and 1961/62-1979/80, in the catchments.

Drainage density was highest in Maseru 2 all three years, followed by Mohales Hoek 1. Mafeteng 1 had the lowest drainage density in 1950, Maseru 1 the lowest drainage density in 1961/62 and 1979/80. The highest extension rate (annual increase in drainage density) during the first period (1950-61/62) was found in Maseru 2, followed by Leribe 1 and 2, and Mohales Hoek 2. The lowest rate was found in Maseru 1. The highest extension rate during the second period (1961/62-79/80) was found in Mafeteng 1, followed by Mohales Hoek 1. The lowest rate was found in Mohales Hoek 2, followed by Maseru 1 and 2. Three of the catchments showed higher extension rate during the second period, compared to the first, namely Maseru 1, Mafeteng 1 and Mohales Hoek 1.

Gully area and expansion, and volume estimates

Figure 4.10 shows the gully area and expansion rate, i.e. increase in gully area per year. For all three years, the largest area covered by gullies was found in Maseru 2, followed by Mohales Hoek 1. The smallest area was in 1950 found in Leribe 2, in 1961/62 in Mohales Hoek 2, and in 1979/80 in Mafeteng 2. The gully area results presented in Table 8 can be seen as absolute figures of the area covered by gullies in the catchments (m^2/km^2), or as a percentage of the catchment area.

Lundén et al. (1986) studied gully erosion in the catchments Leribe 1 (Mathokoane 1), Maseru 1 (Sofonia) and Mohales Hoek 1 (Ha Khitsane). Table 10 gives a comparison between their estimates of gully area in the catchments and the results of this study. The percentages are consistently lower in this study. The largest discrepancies are found in Leribe 1 where expansion between 1950 and 1961 was 2.0 % in this study compared to 1.1 % in the study by Lundén et al. (op cit.), and in Mohales Hoek 1 where expansion between 1961 and 1980 was 2.5 % in this study and 1.0 % in the study by Lundén et al. (op cit.). Since the same method and instrument for measuring gully area were used the discrepancies can only be ascribed to differences in interpretation since the method is subjective. The catchments Leribe 1 and Mohales Hoek 1 have complex gully networks and numerous discontinuous gullies that complicate the interpretations. In addition Mohales Hoek 1 has extensive badland areas. Maseru 1 on the other hand has a relatively limited and simple network of gullies. This may explain why the differences between the two studies are smaller in the case of Maseru 1.

According to this study the expansion rate (annual increase in gully area) during the first period (1950-61/62) was highest for Mohales Hoek 1, followed by Leribe 1 and 2. The expansion rate was lowest in Mohales Hoek 2, Maseru 1 and Mafeteng 1. During the second period (1961/62-79/80) the expansion rate was highest in Mafeteng 1 and Mohales Hoek 1, and lowest in Mafeteng 2. Three of the catchments showed a significantly higher expansion rate during the second period, compared to the first, namely Maseru 1, Mafeteng 1 and Mohales Hoek 2.

The rough volume estimates reveal that the largest volume of sediment (m^3/km^2) has been removed from Maseru 2, followed by Leribe 2 and Maseru 1. The smallest volume of sediment has been removed from Mafeteng 1 and Mohales Hoek 2. The volume may be small despite relatively large gully area, due to shallow gully depths, and the reverse, small area but large volume due to large depths.

Gully heads and their development rate

Maseru 2 has, in all years, the highest number of gully heads (per km²) (Table 8), followed by Mohales Hoek 1, and in 1979/80 also by the two Leribe catchments. In 1950 the lowest number of heads/km² was found in Mafeteng 1, in 1961/62 in Maseru 1, Mafeteng 1 and 2, and in 1979/80 in Maseru 1 and Mafeteng 2.

The largest number of discontinuous gully heads (per km²) was in 1950 found in Mohales Hoek 1, followed by Maseru 2 Leribe 2, in 1961/62 in Leribe 2, followed by Mohales Hoek 1, and in 1979/80 in Leribe 2, followed by Mafeteng 1. In 1950 and 1961/62 Maseru 1, Leribe 1 and Mafeteng 1 had the lowest number of discontinuous gullies. In 1979/80 Maseru 2 had the lowest number, followed by Maseru 1. All catchments have had an increase in discontinuous gully heads since 1950, except Maseru 2 which has shown a slight decrease, indicating that the gullies have fused and become continuous. The increase was largest in Mafeteng 1, followed by Leribe 2, and lowest in Mafeteng 2, followed by Mohales Hoek 1 and Maseru 1.

The percentage of heads at discontinuous gullies for different years is consistently highest in Leribe 2. The percentage was lowest in Leribe 1 in 1950 and 1961/62. In 1979/80 the percentage was lowest in Maseru 2. The percentage has decreased since 1950 in Leribe 2, Maseru 2, Mafeteng 1 and Mohales Hoek 1 and 2. It increased in the other catchments. A decrease in the percentage of discontinuous gully heads indicates that either the discontinuous gullies have fused to form continuous gullies, or that new initiation of gully heads has occurred in the form of gullies extending from already developed gullies rather than as discontinuous gullies along the slope.

The development rate of gully heads (annual increase in heads/km²) was highest in Leribe 1 and 2, and Maseru 2 during the first period (1950-61/62). During the second period (1961/62-79/80) the rate was highest in Mafeteng 1 and Leribe 1, followed by Leribe 2 and Mohales Hoek 1. The rate was lowest during the first period in Maseru 1 and Mafeteng 2, and during the second period in Maseru 1, Mafeteng 2 and Mohales Hoek 2. However, in most cases the differences are slight as regards gully head development rate during the two periods for the different catchments. The largest discrepancies are found in Mafeteng 1 and Mohales Hoek 1, which both showed increased rates, and in Maseru 2 which showed a decrease.

Extension/expansion ratio

Due to the fact that the extension of gullies in a catchment also contributes to an increase in gully area, it is not possible to set a ratio of 1.0 as the limit between dominance of either process. Gully extension may very well dominate if the ratio is less than 1.0. The ratio should rather be used to detect possible trends in the impact of either process between the two periods (1950-61/62, 1961/62-79/80). It should also be noted that the results show the added influence of the two processes respectively, over long periods of time (11-12 and 17-19 years). The dominance of either process may very well have varied frequently during the two periods.

Gully extension was very active during the first period in Maseru 2, Mafeteng 1 and Mohales Hoek 2, and during the second period in Mafeteng 2. The impact of gully expansion appears to have been greater in Maseru 1 and 2, Mafeteng 1 and Mohales Hoek 2, during the later period (giving a decrease in ratio). The ratio increased in the four other catchments.

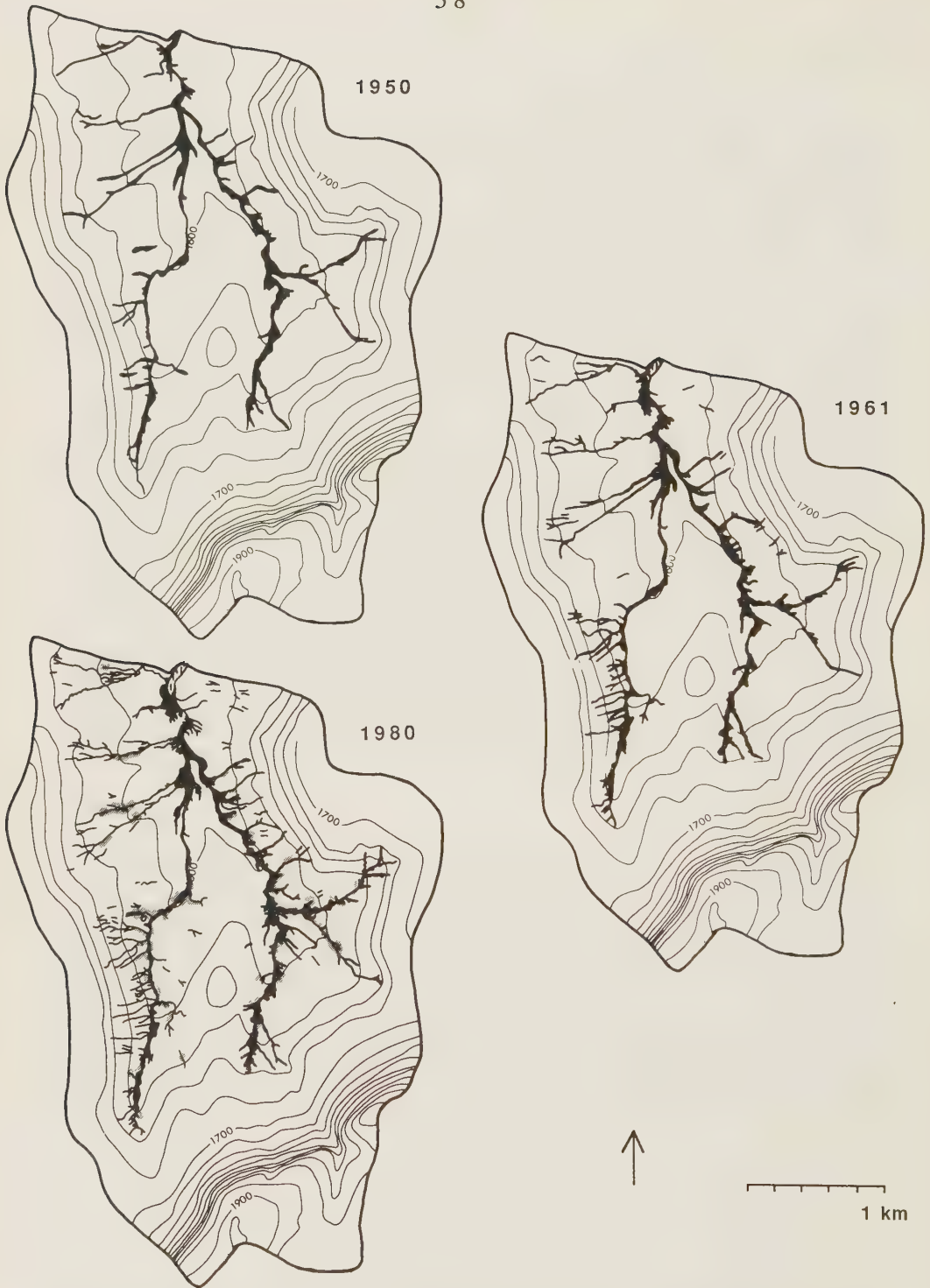


Figure 4.1. Extent of gullies in Leribe 1 (Mathokoane 1) in 1950, 1961 and 1980, and presence of piping along the gullies in 1987 (shaded). The large pipe described in the text is situated at a tributary at a tributary to the western main gully, just below the escarpment (marked with a black circle)(see Fig. 4.11, 4.12).

1950



1961



1980



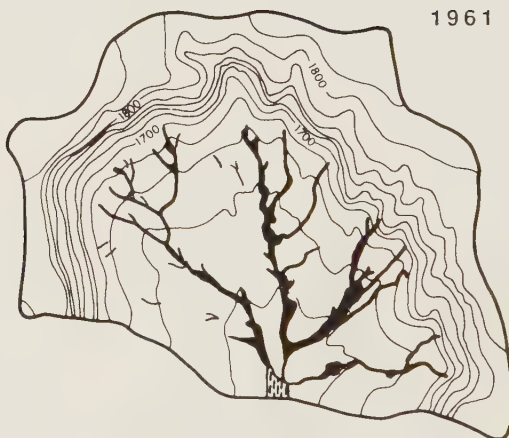
A horizontal scale bar with five equal segments, labeled "1 km" at the right end.

Figure 4.2. Extent of gullies in Leribe 2 (Mathokoane 2) in 1950, 1961 and 1980, and presence of piping along the gullies in 1988 (shaded).

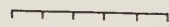
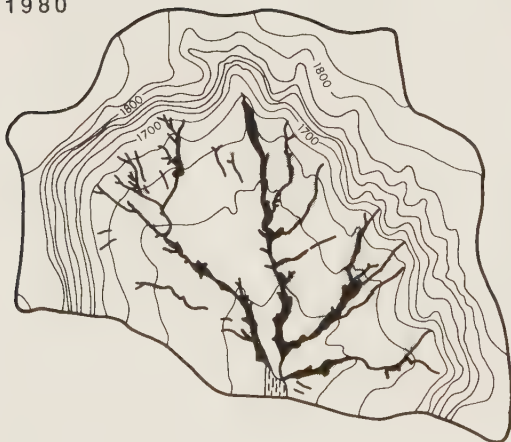
1950



1961



1980



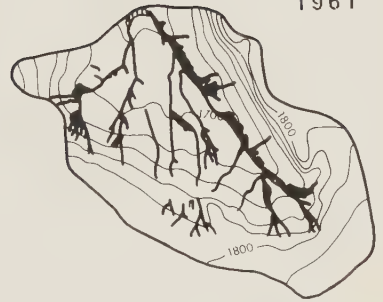
1 km

Figure 4.3. Extent of gullies in Maseru 1 (Sofonia) in 1950, 1961 and 1980, and presence of piping along the gullies in 1987 (shaded).

1950



1961



1980



A scale bar representing 1 km. It consists of a horizontal line with several tick marks, and the text "1 km" is written below it.

Figure 4.4. Extent of gullies in Maseru 2 (Marabeng) in 1950, 1961 and 1980, and presence of piping along the gullies in 1988 (shaded).

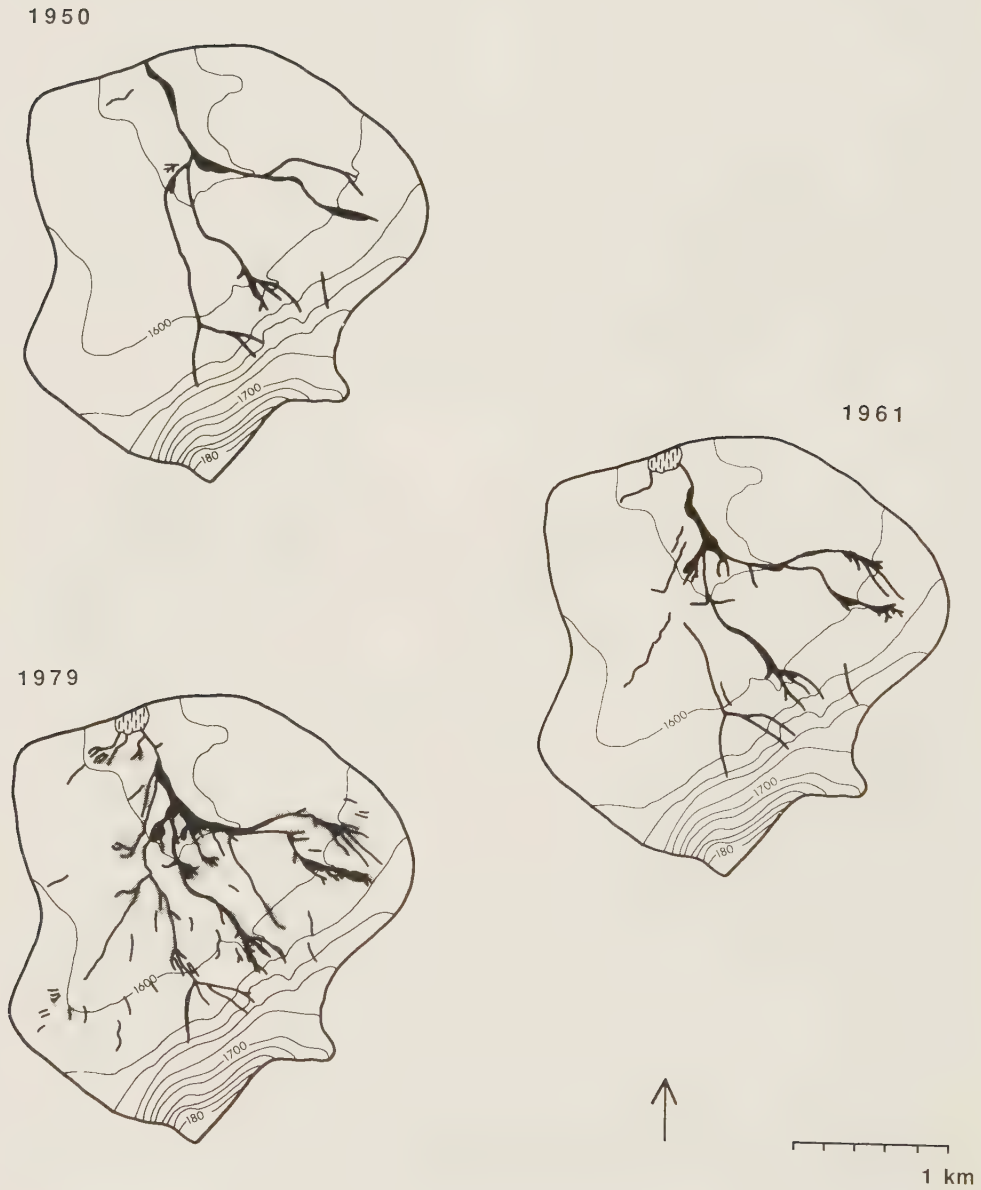
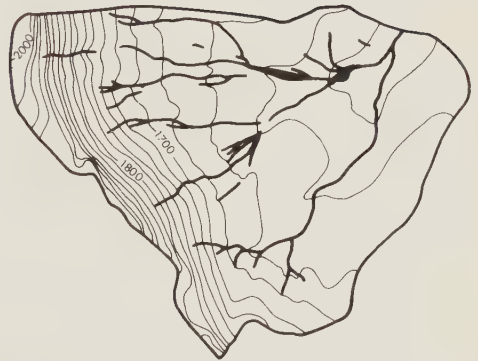


Figure 4.5. Extent of gullies in Mafeteng 1 (Matsoseng) in 1950, 1961 and 1979, and presence of piping along the gullies in 1988 (shaded).

1950



1961



1979

A scale bar representing 1 km, with markings for 0, 0.2, 0.4, 0.6, 0.8, and 1.0 km.
1 km

Figure 4.6. Extent of gullies in Mafeteng 2 (Boleka) in 1950, 1961 and 1979, and presence of piping along the gullies in 1988 (shaded).

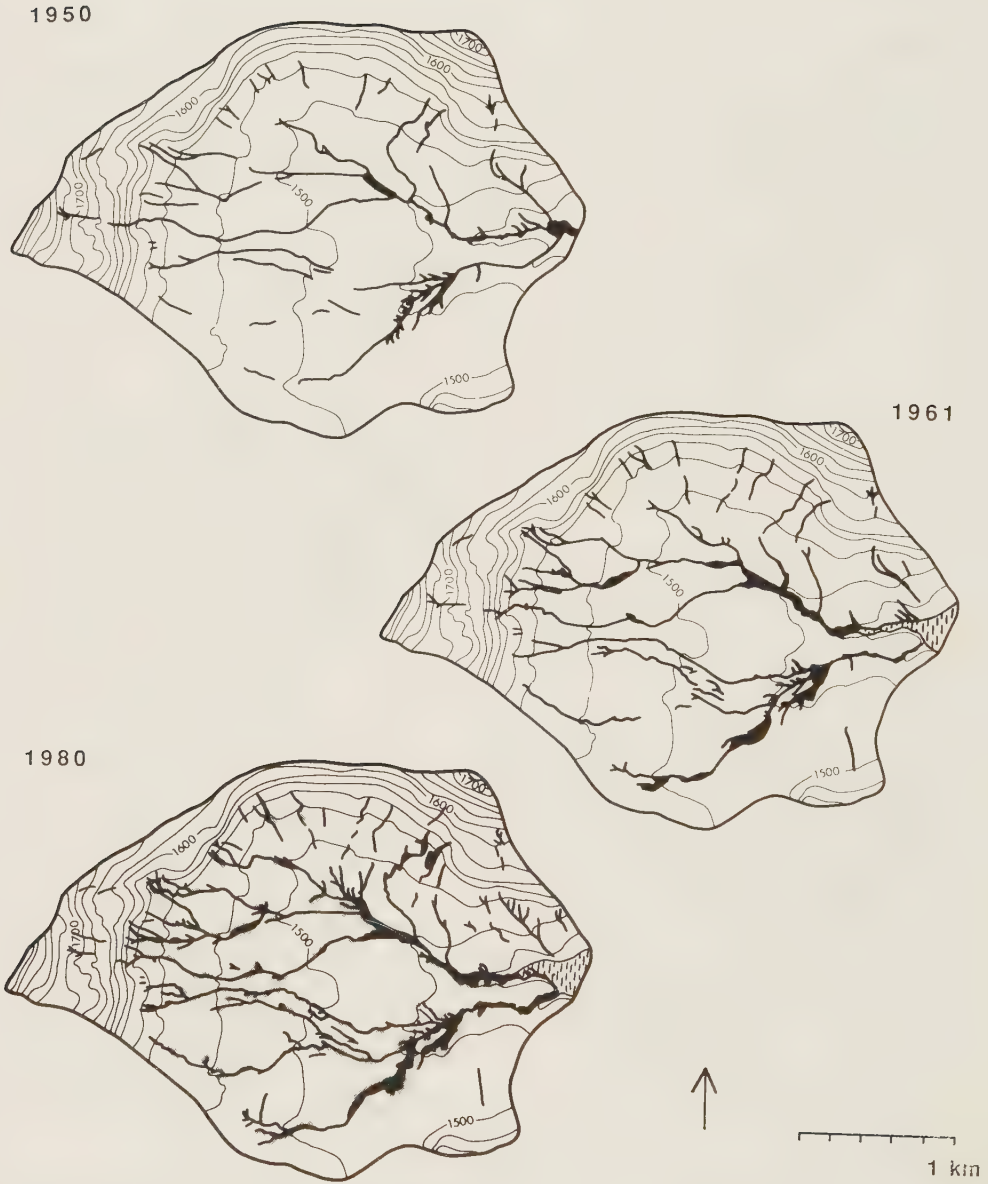


Figure 4.7. Extent of gullies in Mohales Hoek 1 (Ha Khitsane) in 1950, 1961 and 1980, and presence of piping along the gullies in 1987 (shaded).



Figure 4.8. Extent of gullies in Mohales Hoek 2 (Maphutseng) in 1950, 1962 and 1979, and presence of piping along the gullies in 1988 (shaded).

Table 8. Results of the air photo interpretation and gully length, area and head measurements and calculations.

	Leribe		Maseru		Mafeteng		Mohales Hoek	
	1	2	1	2	1	2	1	2
Drainage density (10^3 m/km²):								
1950	1.7	1.9	2.0	4.1	1.6	2.4	3.2	2.0
1961/62	2.5	2.7	2.1	5.1	2.2	3.1	3.9	2.8
1979/80	3.5	3.7	2.6	5.5	3.6	3.9	5.0	3.1
Gully area (10^4 m²/km², or % of catchment area):								
1950	4.6	4.2	5.6	11.9	5.1	4.7	6.3	4.6
1961/62	6.6	6.5	5.8	12.5	5.3	6.2	9.0	4.8
1979/80	7.6	7.7	7.1	13.6	7.7	6.6	11.5	6.8
Gully heads (heads/km²):								
1950	8	6	6	18	4	6	12	8
1961/62	14	13	8	25	8	8	15	13
1979/80	25	23	14	32	19	14	24	18
Discontinuous gully heads (disc. heads/km²):								
1950	0.4	3.0	0.7	3.2	1.2	2.0	4.5	2.0
1961/62	1.6	5.4	1.5	2.8	1.6	2.0	4.7	2.6
1979/80	4.2	8.4	2.0	1.6	6.6	2.7	5.8	3.6
Discontinuous gully heads (% of total number of heads):								
1950	5	47	11	18	33	31	38	24
1961/62	11	42	19	11	21	25	32	21
1979/80	17	36	15	5	34	19	24	20
Volume (10^5 m³/km²):								
1979/80	4.6	5.0	4.8	6.8	2.1	2.8	3.4	2.2
Extension rate (m/km²/year)(1):								
1950-1961/62	69	72	15	86	47	66	58	72
61/62-79/80	53	52	25	26	80	47	61	18
1950-1979/80	59	59	21	48	67	55	60	41
Expansion rate (10^2 m²/km²/year)(1):								
1950-1961/62	18	21	2	6	2	14	25	2
61/62-79/80	5	6	7	6	13	2	13	12
1950-1979/80	10	12	5	6	9	6	17	8
Gully head development rate (new heads/km²/year)(1):								
1950-1961/62	0.6	0.6	0.2	0.6	0.4	0.2	0.3	0.4
61/62-79/80	0.6	0.5	0.3	0.4	0.6	0.3	0.5	0.3
1950-1979/80	0.6	0.6	0.3	0.5	0.5	0.3	0.4	0.3
Extension/expansion ratio (m⁻¹)(1):								
1950-1961/62	0.04	0.03	0.10	0.16	0.26	0.05	0.02	0.38
61/62-79/80	0.10	0.09	0.03	0.04	0.06	0.28	0.05	0.02
1950-1979/80	0.06	0.05	0.04	0.08	0.07	0.09	0.03	0.05

(1) Actual values of drainage density, gully area etc. were used for the calculations, not the rounded figures presented in the table.

Table 9. Summary of the results of the gully length, area and head measurements and calculations in the catchments. The catchments having the highest, second highest and lowest value for each parameter are shown. The results are presented in detail in Table 8.

	1	Ranking 2	8
Drainage density 1979/80	Maseru 2	Mohales Hoek 1	Maseru 1
Gully area 1979/80	Maseru 2	Mohales Hoek 1	Mafeteng 2
Gully heads 1979/80	Maseru 2	Leribe 1	Maseru 1
			Mafeteng 2
Discont. gully heads 1979/80	Leribe 2	Mafeteng 1	Maseru 2
% Discont. gully heads 1979/80	Leribe 2	Mafeteng 1	Maseru 2
Volume (1979/80)	Maseru 2	Leribe 2	Mafeteng 1
Extension rate 1950-61/62	Maseru 2	Leribe 2	Maseru 1
Extension rate 1961/62-79/80	Mafeteng 1	Mohales Hoek 1	Mohales Hoek 2
Expansion rate 1950-61/62	Mohales Hoek 1	Leribe 2	Mafeteng 2
			Mohales Hoek 2
			Maseru 1
Expansion rate 1950-61/62	Mohales Hoek 1		Mafeteng 2
	Mafeteng 1		
Gully head development rate 1950-61/62	Maseru 2		Maseru 1
	Leribe 1		Mafeteng 2
	Leribe 2		
Gully head development rate 1961/62-79/80	Leribe 1		Mafeteng 2
	Mafeteng 1		Mohales Hoek 2
			Maseru 1
Ext./Exp. ratio 1950-61/62	Mohales Hoek 2	Mafeteng 1	Mohales Hoek 1
Ext./Exp. ratio 1961/62-79/80	Mafeteng 2	Leribe 1	Mohales Hoek 2

Table 10. Comparison between the results of the gully area measurements carried out in this study and in a study by Lundén et al. (1986), in the catchments Leribe 1, Maseru 1 and Mohales Hoek. The names of the catchments used by Lundén et al. (op cit.) are presented in brackets.

	1950	Gully area (% of catchment area) 1961	1980
Leribe 1 (Mathokoane 1):			
This study	4.6	6.6	7.6
Lundén et al. (1986)	5.9	7.0	8.0
Maseru 1 (Sofonia):			
This study	5.6	5.8	7.1
Lundén et al. (1986)	6.4	6.7	7.8
Mohales Hoek 1 (Ha Khitsane):			
This study	6.3	9.0	11.5
Lundén et al. (1986)	8.9	12.3	13.3

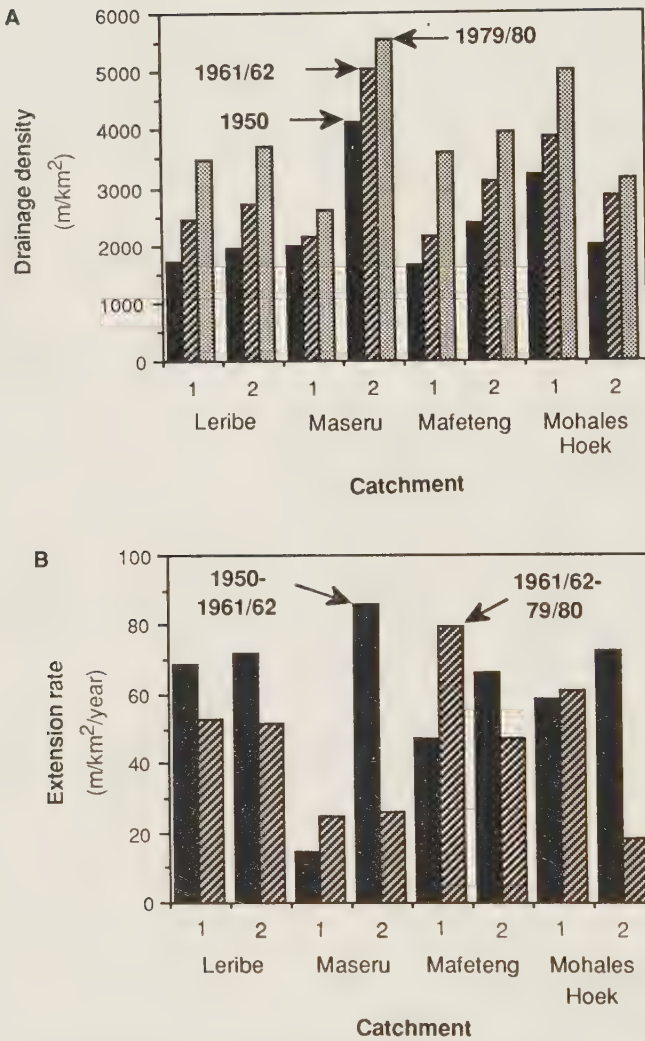


Figure 4.9. A: drainage density in the study catchments in 1950, 1961/62 and 1979/80, and B: annual extension rates (i.e. increase in gully length) during the periods 1950-1961/62 and 1961/62- 1979/80.

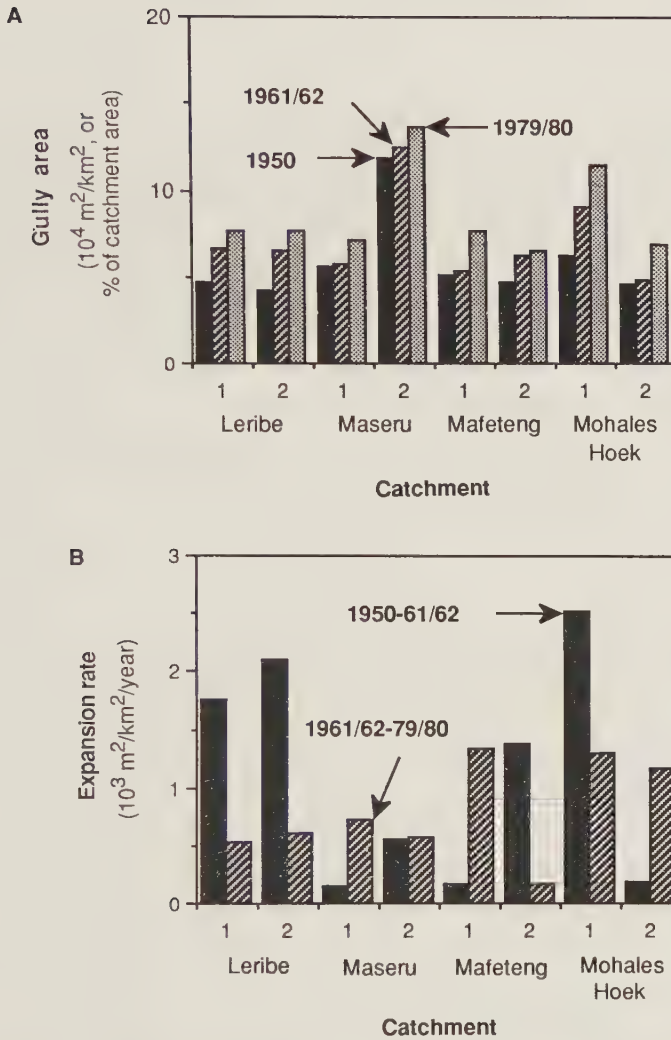


Figure 4.10. A: gully area in the study catchments in 1950, 1961/62 and 1979/80, and B: annual expansion rates (i.e. increase in gully area) during the periods 1950-1961/62 and 1961/62-1979/80.

4.2 Field inventory

The results of the field inventory are shown in Table 11. Table 12 is a summary where the catchments having the highest, second highest and lowest value for each parameter are shown.

Piping

Two types of piping were found in the catchments. A shallow type where the pipes have developed in the clayey B-horizon, and a deeper type where they have developed due to favourable conditions deeper down in the profile (in the parent material). In some cases the two occur together in the same profile. The shallow type is predominating in Mafeteng 1 and Mohales Hoek 1 whereas deep piping is more common in Mafeteng 2 and Mohales Hoek 2, and dominates in Leribe 1 and 2, and Maseru 1. Maseru 2 has very little piping but, where found, it is of the deep kind.

Mafeteng 1 has the highest piping index of the catchments, followed by Maseru 1 and Mohales Hoek 1. Maseru 2 has the lowest index of piping.

Table 11. Results of the field inventory of the catchments.

	Leribe		Maseru		Mafeteng		Mohales Hoek	
	1	2	1	2	1	2	1	2
Piping index	0.07	0.11	0.16	0.01	0.21	0.04	0.09	0.14
Gully heads with piping (%)	11	4	1	1	13	5	3	10
Average slope above gully head (%)	8.2	7.4	7.9	12.4	6.9	8.5	10.2	6.3
Average depth along gullies (m)	6.0	6.6	6.8	5.0	2.8	4.3	2.9	3.2
Average depth at gully heads (m)	2.8	3.2	4.0	3.8	1.8	2.3	2.6	3.1
Gully heads extended to bedrock (%)	10	12	12	29	10	10	21	9
Gully heads cut down to bedrock (%)	20	21	30	61	19	35	28	36
Gully heads in connection with (1)								
terrace (%)	46	59	46	14	39	48	12	58
cultivation (%)	2	2	10	0	15	0	14	4
road/path (%)	4	9	5	4	5	1	7	3
Cross-section at gully heads (see Figure 2.2)(%):								
Fig. 2.2 A/B	55	42	53	46	36	45	49	30
C	23	14	24	14	29	21	19	37
D (2) sediment	9	25	6	4	9	15	12	12
bedrock	5	8	3	33	1	16	3	19
E	0	4	1	0	0	0	3	0
F	7	3	10	3	18	2	10	2
G	0	0	0	0	4	1	2	0
H	1	4	3	0	3	0	2	0

(1) The percentages do not add up to 100 since all gully heads are not found in connection with either of the three.

(2) The shape may be caused either by deposition of sediment in the gully bottom, or by the gully eroding down to the resistant bedrock.

Table 12. Summary of the results of the field inventory in the catchments showing the catchments which have the highest, second highest and lowest value for each investigated parameter. The results are presented in more detail in Table 11.

	1	Ranking 2	8
Piping index	Mafeteng 1	Maseru 1	Maseru 2
Heads with piping	Mafeteng 1	Leribe 1	Maseru 1
Average slope above gully head	Maseru 2	Mohales Hoek 1	Mohales Hoek 2
Average depth along gullies	Maseru 1	Leribe 2	Mafeteng 1
Average depth at gully head	Maseru 1	Maseru 2	Mafeteng 1
Gully heads extended to bedrock	Maseru 2	Mohales Hoek 1	Mohales Hoek 2
Gully heads cut down to bedrock	Maseru 2	Mohales Hoek 2	Mafeteng 1
Gully heads in conn. with terrace	Leribe 2	Mohales Hoek 2	Mohales Hoek 1
Gully heads in conn. with cultivation	Mafeteng 1	Mohales Hoek 1	Maseru 2
Cross-section: U/trapezoidal	Leribe 1	Maseru 1	Mohales Hoek 2
V	Mohales Hoek 2	Mafeteng 1	Maseru 2
Rectangular (sed.)	Leribe 2	Mafeteng 2	Leribe 2
Rectangular (bedr.)	Maseru 2	Mohales Hoek 2	Maseru 2
			Mafeteng 1

Gully head processes and morphology

Maseru 1 has the highest value of average depth and head height, followed, in the former case, by Leribe 1 and 2, and in the latter case, by Maseru 2. Maseru 2 and Mohales Hoek 1 have the steepest average slope above the gully heads. This would indicate that gullies have extended further up the slopes in these two catchments, reaching closer to the escarpment or water divide.

The highest percentage of heads that have extended to bedrock, i.e. reached their ultimate extension, is found in Maseru 2 and Mohales Hoek 1, again indicating that the gullies have extended far upslope. The former also has the highest percentage of gully heads that have cut down to bedrock, followed by Mohales Hoek 2, and Mafeteng 2. In all catchments, except Maseru 2 and Mohales Hoek 1, a large percentage of the gully heads are found in connection with terraces. The low percentage in Maseru 2 and Mohales Hoek 1 is probably due to the fact that these gullies have extended past cultivated fields and terraces. It does not necessarily imply that the terraces are functioning more effectively or are well maintained in these two catchments. As mentioned in Section 3.3.1 it is often impossible to determine whether or not the terrace was the original cause of the gully headcut but, nevertheless, the terrace may, by concentrating the flow, have assisted in the erosion process. Mafeteng 1 has the highest percentage of gully heads found in connection with cultivation.

In all catchments, except Mohales Hoek 2, the most common cross-section at the gully heads is the U/trapezoidal shape (see Fig. 2.2 A,B), where more or less debris remains along the gully walls. The percentage is highest in Leribe 1, followed by Maseru 1. Mohales Hoek 2 has the highest percentage of V-shaped gullies, followed by Mafeteng 1. In the former case this is probably caused by relatively resistant soils (no soil map is available). In the latter case, the prominence of piping is a contributing factor.

Leribe 2, Maseru 2 and Mafeteng 2 have the highest percentages of gully heads of a rectangular cross-section. In Maseru 2 most of the gullies have cut down to the resistant bedrock, in Leribe 2 the shape is caused by deposition of sediment on the gully floor. In Mafeteng 2 both types occur.

Vegetation

Vegetation may be found on the debris along the walls in the U/trapezoidal shaped gullies. In most cases it has probably been carried there with the fallen material and will be removed in due time as the material is eroded away. In some cases, however, it is well established and appears to have stabilized the gully. Bushes and small trees are found in and along some of the main gullies in Leribe 1 and 2, and Maseru 1 and 2, most of them have probably been planted. The other catchments have no bushy vegetation in or along the gullies, only grass and possibly some shrubs.

In Leribe 1 and 2, and Maseru 1 patches of small trees and bush (commonly poplars), are found along the gullies, close to the rims. It is common to find these small isolated patches in pipe inlets, apparently having sunk as the pipe roof collapsed. Thus it seems probable that the poplars, if not the sole cause of piping in those particular places, through their deep and penetrating root systems have certainly promoted the development of the deep kind of piping and subsequent gullying.

4.3 General description of gully erosion in the catchments

Judging by the results of the gully length and area measurements presented in Table 8, and shown in Figure 4.9 A and 4.10 A, it is possible to group the catchments in three erosion classes, based on the air photo interpretations. All catchments are, and were already in 1950, badly dissected by gullies and the classification is therefore only relative. Maseru 2 and Mohales Hoek 1 are, and have consistently been, the most severely eroded. In 1950 the other catchments were quite similar with respect to the severity of erosion, Mafeteng 2 had a slightly higher drainage density. In 1961/62 only Maseru 1 and Mafeteng 1 were slightly eroded. In 1979/80 Maseru 1 was still lagging behind, being the least eroded catchment.

Leribe 1 (Mathokoane 1)

The gully development in the catchment is shown in Figure 4.1. About 50 % of the soils in this catchment are duplex. They are found entirely in the basin below the escarpment where they cover the major part (see Fig. 3.14). This is also where the gullies are found.

Most of the gully development since 1950 has occurred in the form of gully heads extending from the two main gullies, eastward and westward respectively. There has also been considerable widening of the main gullies, the eastern one in particular. The large interfluvium in the centre of the catchment is virtually untouched by gully erosion, and so are the plateaus surrounding the basin.

Several of the gullies found below the escarpment in the western part of the basin have developed in the soil unit "Rough broken land". This is a mixture of weakly developed and highly erodible soils, derived from shale and sandstone (Cons. Div., 1979b). Some of these gullies have not yet cut down to bedrock. This is also the case with the tributary gullies below the escarpment further north, and for several of the gullies in the zone where the largest tributary enters the eastern main gully. At several points along the main gullies, sandstone outcrops in the gully bottom, forming a threshold with an abrupt increase in gully depth downstream.

Piping is found along stretches of gullies in the whole catchment. Piping is of the deep type, creating stretches of badlands, particularly along the eastern main gully. A large pipe was found, which enters into one of the gullies below the western escarpment (see Fig. 4.1). The outlet is almost at the level of the gully floor, about 6 m below the soil surface (Fig. 4.11, 4.12). It has developed in shale on silt/mudstone, topped by coarse sandstone alluvium. The pipe is about 1 m high and 0.4-0.8 m wide and extends for an unknown distance upslope. Inside the pipe, several large cracks in the alluvium are visible, sometimes reaching up to the soil surface. The pipe shows a distinct flow pattern, apparently following cracks and fissures.

The gullies in the catchment are usually deep. Depths exceeding 10 m are not uncommon in the main gullies, diminishing towards the dam in the north. Some of the tributaries in the northwest have depths exceeding 5 m.

The most common cross-sections are V-shaped, although in the main gullies, debris along the walls gives rise to a narrow U/trapezoidal shape with steep walls. Towards the dam, deposition of sediment on the gully floor creates a rectangular cross-section.

Bushes and small trees are common along the western main gully and some of its major tributaries in the north, and along the southern-most part of the eastern main gully and the northern branch of its major tributary.

Leribe 2 (Mathokoane 2)

The gully development in the catchment since 1950 is shown in Figure 4.2. Two areas in the catchment, which have experienced severe gully extension since 1950 are the north-eastern and south-western parts. Considerable expansion of the main gullies has occurred, but the central interfluvium has been left almost unaffected by gully erosion.



Figure 4.11. The outlet of the large pipe in Leribe 1. The outlet (at the bottom of the photo) is slightly above the level of the gully floor, about 6 m below the soil surface. The pipe has developed in shale on silt/mudstone, topped by coarse sandstone alluvium. The outlet is about 1 m high and 0.4-0.8 m wide (March 22, 1988).



Figure 4.12. Inside the large pipe in Leribe 1. The pipe shows a distinct flow pattern and apparently has developed along cracks and fissures. It extends for an unknown distance upslope. The pipe is narrow but high and some of the large cracks in the sandstone alluvium reach up to the soil surface above (March 22, 1988).

Piping is mainly of the deep type and found along gully stretches over the whole catchment, except for the northern-most part. Shallow piping is found along some of the discontinuous gullies in the south-west. A large pipe about 1 m in diameter was found in this catchment, too. It has developed in similar material as the one in Leribe 1. About 20 m upstream from the pipe outlet, sandstone is exposed on the gully bottom, forming a threshold. Directly downstream from this bedrock outcrop there is an abrupt increase in gully depth and the gully has eroded down to the silt/mudstone. This sequence is found in several other locations in the catchment. Piping is frequently found downstream from these spurs, though the pipes are less spectacular than the one described.

The largest depths are found along the main gullies, frequently exceeding 10 m, but diminishing towards the valley mouth in the north. Some of the tributaries in the north-east have depths exceeding 5 m.

V-shaped cross-sections dominate along the gullies, although along the main gullies it may have developed into a U/trapezoidal shape due to debris along the walls. Due to

deposition of sediment on the gully floor the rectangular shape is found towards the valley mouth in the north. Bushes and small trees are common in and along all major gullies.

Maseru 1 (Sofonia)

The gully development in the catchment since 1950 is shown in Figure 4.3. Most of the gully extension since 1950 has occurred below the escarpment in the western part of the catchment. The other parts of the drainage system have experienced some extension, but mainly expansion. Most of the gullies have cut down to bedrock, except for a few in the south-west and west. Two distinct interfluvies, virtually unaffected by gully erosion, are found in the centre of the catchment. No gullying is found on the plateau above the escarpment.

The catchment has the lowest portion of duplex soils among the four catchments for which soil maps are available. Most of the gullies have developed in duplex soils. An area in the north-west has Matela and Maliele soils (non-duplex) and is severely gullied. Piping is also found in this area. The non-gullied interfluvies have Berea soil. Piping is predominantly of the deep type, and is found along gully stretches in the whole catchment.

Gully depths diminish towards the dam in the south. The largest depths, greater than 10-15 m, are found along the central main gully and in some gullies in the north-western part of the basin.

The cross-sections along the gullies are dominantly V- and U/trapezoidal shaped. Due to deposition, the rectangular shape is found close to the dam. There is widespread grass vegetation on the main gully floors towards the dam, and the gullies appear to be relatively stable, at least as far as downcutting is concerned. Trees and bushes are found in and along some of the major gullies, mainly in the east.

One gully, formerly extending about 20 m from the eastern main gully towards the escarpment, in February 1988 extended 25 m headwards. This was caused by excessive rainfall during February, about 50 mm above normal, following the dry month of January, about 70 mm below normal. The gully has a depth of 6 m and a width of 4-5 m, i.e. a volume of roughly 600 m³ was removed.

Maseru 2 (Marabeng)

The gully development in the catchment since 1950 is shown in Figure 4.4. Most of the gully development since 1950 has occurred in the form of expansion. Along the main gully, but also along the tributaries. One area in the south on the slope reaching up on the plateau has experienced severe expansion since 1950. The gullies are shallow in this area (1-4 m) and have cut down to bedrock. Expansion is rapid and more and more of the bedrock is exposed. Further up, on the plateau, no gullies are found. Most of the gullies in the catchment have cut down to bedrock.

Piping, of the deep kind, was only detected in two locations, both along the main gully. The largest depths (5-10 m) are found along the main gully and in the upper parts of the tributary gullies in the west.

The rectangular cross-section is common because of bedrock exposed on the gully floors. Towards the dam, some sedimentation has occurred in the gullies, also giving rise to a rectangular shape. The deposits have a grass cover. V-shaped cross-sections are mainly found in the upper reaches of the western tributaries. Along the main gully the U/trapezoidal shape is common due to debris along the walls. Scattered bushes and small trees are found along the main gully.

Mafeteng 1 (Matsoseng)

The gully development in the catchment since 1950 is shown in Figure 4.5. This catchment has the largest portion of soils of a duplex nature (75 %) of the catchments of which soil maps are available. Gully erosion is almost entirely confined to these soils. However, one area in the north, mainly with duplex soils, is unaffected by gully erosion.

The central part of the catchment has experienced severe gully extension since 1950. Many of the gullies appear to have developed along field boundaries. Expansion has mainly occurred along the main gully and in the central area.

This catchment has the highest piping index of all the catchments. Piping is both shallow and deep (Fig. 4.13, 4.14). The eastern part of the catchment, below the escarpment, is severely affected by both types of piping. Depths vary between the tributaries in this area and none of them have yet cut down to bedrock. It is reasonable to assume that erosion in this area will continue until the local baselevel is reached.

In the centre of the catchment, shallow piping has created large badland areas, with depths ranging from less than one metre to 2-3 m. In the western-most part of the catchment, several discontinuous gullies have developed due to shallow piping and the area is probably slowly turning into badland.

Gully depths do not usually exceed 5-6 m, being largest in the upper reaches of the drainage system, diminishing towards the dam. Most of the gullies have not yet cut down to bedrock. Along the two major tributaries in the west, bedrock is exposed at several locations along the gully bottom, particularly in the upper reaches of the gullies.

V-shaped cross-sections are common along the gullies, particularly in the eastern portion of the drainage system, which is subject to piping. U/trapezoidal cross-sections are found in the wider portions of the main gullies. The bottom of the main gullies, closer to the dam, have a dense grass cover and appear to be relatively stable.



Figure 4.13. Gully erosion caused by shallow piping in Mafeteng 1. The small pipes have developed in the B-horizon, at a present depth of 0.3-0.4 m. The A-horizon has been removed by erosion. The flow pattern reflects the columnar structure of the B-horizon, following cracks and fissures (March 21, 1988).



Figure 4.14. Large pipe inlets in a zone with deep piping in Mafeteng 1. The pipe roof has collapsed at several points and the pipe is developing into an open and continuous gully. The gully drains into the photo (March 21, 1988).

Mafeteng 2 (Boleka)

The gully development in the catchment since 1950 is shown in Figure 4.6. Most of the gully extension and expansion since 1950, have occurred in the central part of the catchment. Some expansion has also taken place along the lower portion of the northern main gully. The interfluvium north of the southern main gully is almost unaffected by gully erosion.

Sandstone outcrops at several points along the main gully floors, forming more or less prominent thresholds. Downstream from the larger thresholds, the gully depth increases abruptly. Some of the tributaries in the west, leading to the southern main gully, have not yet cut down to bedrock.

Both types of piping are found in the catchment, the deep type dominating slightly. The shallow type is found in the central part of the drainage system, just above a large sandstone outcrop. In some places here, the shallow piping is due to bedrock acting as an impermeable layer.

Large depths (> 10 m) are found along the lower portion of the northern main gully, and in the western-most reaches of the southern main gully. The dominant cross-sections along the gullies are U/trapezoidal, the rectangular shape appearing at some points along the main gullies due to exposed bedrock or deposition.

Mohales Hoek 1 (Ha Khitsane)

The gully development in the catchment since 1950 is shown in Figure 4.7. Most of the gully erosion is found in duplex soils. The development since 1950 is relatively evenly distributed over the catchment. There are, however, two areas in the centre of the catchment,

two interfluvies between major gullies, where gullying is only slight. The soils on these interfluvies are partly duplex but mainly of the Matela series, and erodibility is moderate. Most of the gully expansion has occurred along the two main gullies.

In general the gullies have cut down to bedrock. Some of the small tributaries to the southern main gully and some of the smaller gullies in the south-west have not yet done so. Bedrock outcrops along the main gully floors at several points, forming thresholds with an abrupt increase in gully depth downstream.

Both types of piping are found in the catchment but the shallow type dominates. Piping is found along gully stretches in most of the catchment. The northern part of the drainage system does not have any visible piping. The soils in that area belong to the Tsiki series.

The southern-most part of the drainage system is severely affected by both types of piping. This area has experienced considerable widening since 1950, apparently by fusion (sideways) of small tributary gullies developed through piping. This badland area has developed in Maseru soil, and the A-horizon has been completely removed. The area between this badland zone and the southern colluvial slope was cultivated in 1950, judging by the air photos. Cultivation was discontinued sometime during the 50s. The area is now used for grazing, but is severely overgrazed and sheet eroded.

The largest gully depths (5-10 m) are found in the badland area in the south, downstream from the bedrock outcrops in the main gullies, and in the upper reaches of some of the tributary and discontinuous gullies in the north-east and in the west.

The V- and U/trapezoidal cross-sections are common along the gullies, the former more prevalent in the northern part of the catchment. The rectangular shape is found towards the dam due to deposition of sediment, and along some stretches of the main gullies due to exposure of bedrock on the gully bottom.

Mohales Hoek 2 (Maphutseng)

The gully development in the catchment since 1950 is shown in Figure 4.8. Most of the gully extension since 1950 has occurred in the central part of the catchment with gullies now forming tributaries to the southern main gully. These gullies have not yet cut down to bedrock. The interfluvie between the two main gullies, apart from this, is to a large extent unaffected by gully erosion. Expansion has mostly occurred along the main gullies. Bedrock outcrops in several places along the main gully floors, forming thresholds with gully depths increasing abruptly downstream.

Both types of piping are found in the catchment, the deep type is slightly more common. Shallow piping is found in the upper reaches of the northern main gully, and along some of the tributaries (from the south) to the southern main gully. Deep piping appears to be the cause of the tributaries on the interfluvie mentioned above.

Gully depths are moderate. The largest depths (6-8 m) are found downstream from the bedrock outcrops in the main gullies, and along the tributary on the interfluvie.

V-shaped cross-sections are common in the tributaries where piping is found. The U/trapezoidal shape is common along the main gullies where debris remains along the walls. The rectangular shape is found on the bedrock thresholds and in other locations where the bedrock is exposed on the bottom and the debris has been effectively removed.

4.4 Data processing and grid square analysis

This section first provides the results of the inventory of sheet and gully erosion using the SARCCUS method (Anon., 1981); secondly the results of the grid square analyses of parameters related to gully erosion in the four catchments of which soil maps are available; and thirdly, the results of the Spearman ranking correlation coefficient analyses for the same four catchments. The results of the grid square analyses of slope in the 8 catchments are shown in Figure 3.11, and the averages are presented in Table 4.

4.4.1 Sheet and gully erosion inventory according to the SARCCUS classification

The analysis of sheet erosion using grid squares proved to be very difficult. The quality of the air photos from different years differ immensely in sharpness, greytone, paper quality and shadows. The accuracy of the results is therefore somewhat limited. The difference in quality is smaller between the air photos of the different catchment taken the same year. The results should, therefore, rather be seen as a comparison between the catchments year by year, and not as precise measurements of the increasing sheet erosion over the years in the separate catchments.

This problem does not apply when using grid squares and the SARCCUS methodology for analysing the extent of gully erosion, as this is less dependent on for example the greytone of the air photos. The delineation of the gullies and classification of the grid squares according to the SARCCUS method proved to be fairly easy. One problem with the method is, however, that the classification (5 classes) to a certain extent filters out the extremes. The results of the gully erosion (SARCCUS) grid square analysis are therefore not as exact as the direct measurement of the gully length in each grid square.

The grid square inventory of sheet and gully erosion was carried out in all 8 catchments. The percentage of each class and the averages for each catchment are presented in Table 13 and 14, and summarized below.

Sheet erosion (SARCCUS classification)

The results of the sheet erosion inventory reveal that in 1979/80 Leribe 2, Mohales Hoek 1, Leribe 1 and Maseru 2, in descending order had the highest averages. In Leribe 2 the high average is to a large extent caused by rock stripping (removal of the thin soil cover, and exposure of bedrock (Schmitz, 1984)) on the escarpment. This process is also very prominent in Maseru 1 and Mafeteng 2. In Mohales Hoek 1 the high average can to a greater degree be ascribed to severe sheet erosion in the flatter parts of the catchment, and the complete removal of the A-horizon. In Maseru 2 both types of sheet erosion are prevalent.

Leribe 2 and Mohales Hoek 1 have the highest averages of sheet erosion in 1950, 1961/62, and 1979/80. Mohales Hoek 2 consistently has low averages, as do Maseru 1, and the two Mafeteng catchments.

A comparison of the results of this study and the results of Strömquist et al. (1986) and Strömquist and Larsson (1988) reveal some discrepancies, for example in the case of Leribe 2, the two Maseru catchments, and Mohales Hoek 1. Black and white air photos were used in this study for the sheet erosion survey, while the other two are based on colour air photos. The limitations of the black and white photos as to paper quality, sharpness etc., have been discussed above. The sheet erosion surveys carried out in the other two studies gave different results in the two catchments used, despite using the same type of material. Although the number of observations is small (only 8 and 2), the discrepancies between the results of the three studies illustrate the danger of comparing results obtained using different materials and interpreters. The problem may exist but is not as great for gully erosion since the interpretations are then less subjective.

Gully erosion (SARCCUS classification)

The gully erosion inventory using the SARCCUS classification produced some interesting findings. Mohales Hoek 1 consistently has the highest average, followed in 1950 by Maseru 1, and in 1961/62 and 1979/80 by Maseru 2. The lowest values are found in Leribe 2 and the two Mafeteng catchments in 1950, in Mohales Hoek 2 in 1961/62. In 1979/80 the lowest values are found in Mohales Hoek 2, Leribe 1, Leribe 2 and Mafeteng 2.

The results deviate somewhat from the direct measurements of gully area in the catchments presented earlier (Table 8). They showed that Maseru 2 was by far the most severely in all years, followed by Mohales Hoek 1. Maseru 1 appears to have received a slightly too high value of erosion in the SARCCUS classification, and Mafeteng 1 a slightly too low value. As mentioned earlier in this section, the use of classes for gully erosion classification has a filtering effect and the method is not as exact as the direct measurement of

gully area in a catchment. This is probably the cause of the discrepancies in the results from the two inventories.

Strömquist and Larsson (1988) used the same method (SARCCUS classification) but the colour air photos from 1983 to study gully erosion in the two Maseru catchments. The results of their study and the present one correlate well.

4.4.2 Grid square analysis of catchment and gully characteristics

In addition to the SARCCUS sheet and gully erosion, grid square analyses of 7 other parameters (listed in Table 7) were carried out in the four catchments of which soil maps are available. Only the air photos from 1979/80 were used. For all parameters except gully length, number of gully heads and slope, class limits were set and classes used in the inventory (3-5 classes). These are described in detail in Appendix 2. For all parameters a higher class indicates a higher potential influence on gully erosion (e.g. erodibility or extent of duplex soils) or, for example, a higher degree of piping or larger gully depth. The results are presented as averages of all grid squares in each catchment, and as averages of the grid squares in which gully erosion is evident. The results are presented as averages in Table 15 and summarized below.

Gully length

The gully length in each grid square was measured and the averages calculated. The results correlate well with the drainage density measurements presented earlier (Table 8). Mohales Hoek 1 has the highest gully length average (m/grid square) of the four analysed catchments, followed by Mafeteng 1 and Leribe 1. Maseru 1 has the lowest average. If the value of average gully length is used to compute the total gully length in the catchments, i.e. average gully length in the grid squares times the number of squares, a slightly too low value is obtained compared to the more continuous measurement of gully length in the catchment as a whole. This is due to errors in the measuring procedure for the former method, e.g. gully stretches that fall under the lines in the grid. Thus, in each grid square the gully length is slightly underestimated and the error is magnified when all grid squares are analysed. The error is of the same magnitude in all four catchments and, hence, does not affect the results of the statistical analysis.

If those grid squares are singled out where gullies are present and an average is determined for these, a slightly different pattern emerges. Leribe 1 has the highest average, followed by Mafeteng 1. Maseru 1 and Mohales Hoek 1 have the lowest averages. The average increases the most in Leribe 1 and Maseru 1 during this transformation, from the average of all grid squares to the average of grid squares where gullies are found. This would indicate that in the zone where gully erosion is present in the catchments, the network is denser in Leribe 1 and Maseru 1, than in Mafeteng 1 and Mohales Hoek 1. For each catchment as a whole, on the contrary, gullying is more severe in Mohales Hoek 1 and Mafeteng 1.

Piping, gully depth and gully heads

There is no point in comparing the values of piping and gully depth as averages of all grid squares in the catchments, since the two parameters are entirely dependent on the presence of gully erosion. The average piping class of the grid squares with gullies is consistent with the piping indexes for each of the four catchments, calculated and presented in Table 11.

Piping is most prominent in Mafeteng 1 and Maseru 1, and less prominent in Mohales Hoek 1 and Leribe 1. Maseru 1 has by far the highest average of gully depth of the four catchments, followed by Leribe 1.

The gully head averages (number of heads/grid square) are also consistent with the results for each of the catchments, presented in Table 8 when calculated for all grid squares. The highest averages are found in Leribe 1 and in Mohales Hoek 1. Maseru 1 has the lowest average. If calculated as averages of the grid squares with gullies the average is by far the highest in Leribe 1. The value is slightly higher in Maseru 1 than in Mafeteng 1 and Mohales

Hoek 1. This again indicates that in the gully eroded zones of the different catchments, gullying is more concentrated in Leribe 1 than in the other three catchments.

Erodibility and duplex soils

The soil erodibility as an average of all grid squares is highest in Mafeteng 1, followed by Leribe 1 and Mhales Hoek 1. Maseru 1 has the lowest erodibility. Mafeteng 1 also has the highest average of duplex soils, followed by Mhales Hoek 1 and Leribe 1. Maseru 1, again, has a lower average. The pattern is the same if calculated as an average of the grid squares with gullies.

A comparison between the average value of piping in the grid squares with gullies and the average value of duplex soils reveals that Mafeteng 1 has the highest average of both parameters while Maseru 1 has the second highest average of piping but the lowest average of duplex soils. Mhales Hoek 1 is second in duplex soils, but third in piping, and Leribe 1 is third in duplex soils and fourth in piping.

Slope

The highest average slope of all grid squares is found in Maseru 1, followed by Mhales Hoek 1 and Leribe 1. Mafeteng 1 has the lowest average. For the grid squares with gullies the pattern is the same. Since Leribe 1 and Mafeteng 1 have the highest averages of gully length for grid squares with gullies, but the lowest average of slope, while the reverse is valid for Maseru 1 and Mhales Hoek 1, the results indicate that gully erosion is not dependent on slope.

Landuse

This classification is based on the vegetation cover for different types of landuse. It is very rough and assumes that areas with settlements have a higher runoff potential, and consequently are more erosion prone than cultivated and grazed areas. The latter was assumed to be least vulnerable to erosion of the three. This ranking may be disputed, at least for the latter two, but as an average over the year, the ranking is probably relevant. The cultivated fields are extremely vulnerable to erosion after the stubble has been removed at the end of the growing season (May-July), through grazing or in order to be used for fuel, and until the new crop has started to sprout in December. The livestock is moved to the foothills and mountains for the rainy season and the grazed areas in the lowlands are left relatively undisturbed during this period. The erosion potential is therefore lower than for the cultivated areas. Grazed areas were considered to be least vulnerable.

The settlements are usually found on top of or right below the escarpment, and the grazed areas are found on the escarpment and in areas where cultivation is impossible, due to steep slopes or poor soils, or on terraces. The landuse index is highest in Mafeteng 1 and lowest in Mhales Hoek 1, reflecting the large portion of cultivated areas in the former, and the large portion of colluvial slopes and grazed areas in the latter area.

Sheet and gully erosion according to the SARCCUS classification in relation to other parameters

The results of the inventories of sheet and gully erosion using the SARCCUS classification system have already been presented (Table 13 and 14) and summarized. A few additional results are worth mentioning. The sheet erosion average in all catchments except Maseru 1 increases when it is based on grid squares with gullies compared to all grid squares. As mentioned earlier, the average value of sheet erosion in Maseru 1 is to a large extent due to a high degree of rock stripping on the escarpment (i.e. removal of the thin soil cover on the bedrock surface). Sheet erosion in the flatter parts of the catchment is not as severe as in the flatter areas of the other three catchments (see Fig. 4.15). Gullies are found in the flatter parts of the catchments, consequently the average of sheet erosion increases in Leribe 1, Mafeteng 1, and Mhales Hoek 1, when the matrix of grid squares with gullies is analysed.

Table 13. Results of the grid square inventory of sheet erosion in the 8 catchments using the SARCCUS classification system (see App. 2). Five erosion classes were used, ranging from no apparent erosion (class 1) to very severe erosion (class 5). The results are presented as percentages of each class in the catchments for 1950, 1961/62 and 1979/80, and as average erosion classes for all grid squares in each catchment. In addition, the dominating class/classes in the catchments are provided and compared with the results of two earlier studies (Strömquist et al. 1986; Strömquist and Larsson, 1988), where colour air photos from 1983 were used.

	Leribe		Maseru		Mafeteng		Mohaies Hoek	
	1	2	1	2	1	2	1	2
Sheet erosion 1950 (% of catchment area):								
Class 1	1.9	0	2.1	1.1	1.2	0	0	0
2	12.8	1.0	22.2	5.6	6.2	4.3	2.6	4.8
3	41.5	45.4	48.7	43.3	57.4	69.4	39.8	67.6
4	28.1	28.6	18.5	31.1	27.2	21.3	32.3	27.6
5	15.7	25.0	8.5	18.9	8.0	5.0	25.3	0
Sheet erosion 1961/62 (% of catchment area):								
Class 1	2.4	0	0	0	0	0	0	0
2	4.8	1.8	4.4	3.4	7.5	4.8	0.5	2.8
3	37.4	25.9	52.2	45.0	50.4	49.2	27.3	63.5
4	35.1	39.4	27.8	25.8	26.4	32.5	33.3	27.1
5	20.3	32.9	15.6	25.8	15.7	13.5	38.9	6.6
Sheet erosion 1979/80 (% of catchment area):								
Class 1	1.7	0	0.5	0	0	0	0	0
2	4.2	1.0	5.9	1.1	3.6	3.2	0	2.2
3	26.8	24.5	38.4	38.0	32.4	38.4	26.4	44.8
4	35.3	32.8	31.4	29.9	43.1	36.8	32.6	43.6
5	32.1	41.7	23.8	31.0	20.9	21.6	40.9	9.4
Average sheet erosion class:								
1950	3.4	3.8	3.1	3.6	3.4	3.3	3.8	3.2
1961/62	3.7	4.0	3.6	3.7	3.5	3.6	4.1	3.4
1979/80	3.9	4.2	3.7	3.9	3.8	3.8	4.1	3.6
Dominating class:								
1950	3	3	3	3	3	3	3	3
1961/62	3/4	4	3	3	3	3	5	3
1979/80	4/5	5	3	3	4	3/4	5	3/4
1983 (1)	3	2	4	4	3	4	3	4
1983 (2)	-	-	2	2	-	-	-	-

(1) Strömquist et al., 1986.

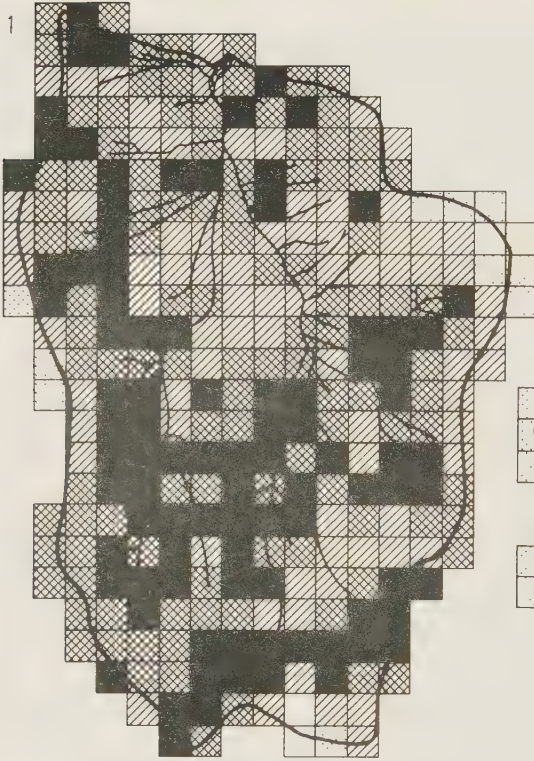
(2) Strömquist and Larsson, 1988.

Table 14. Results of the grid square inventory of gully erosion in the 8 catchments using the SARCCUS classification system (see App. 2). Five erosion classes were used, ranging from no apparent erosion (class 1) to very severe erosion (class 5). The results are presented as percentages of each class in the catchments for 1950, 1961/62 and 1979/80, and as average erosion classes for all grid squares in each catchment. In addition the dominating class/classes in the catchments are provided and compared with the results of an earlier study of two of the catchments (Strömquist and Larsson, 1988), where colour air photos from 1983 were used.

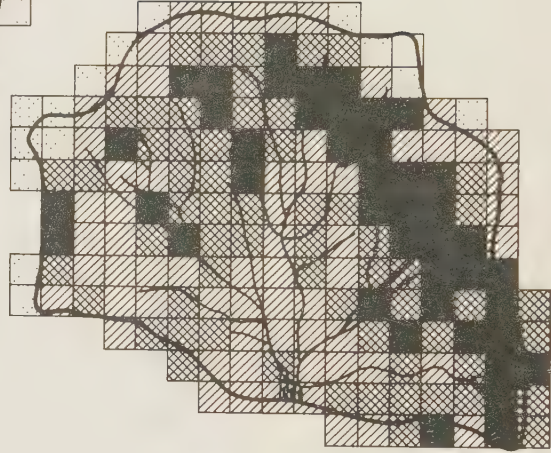
	Leribe		Maseru		Mafeteng		Mohales Hoek	
	1	2	1	2	1	2	1	2
Gully erosion 1950 (% of catchment area):								
Class 1	28.7	40.1	21.6	45.9	36.0	34.7	13.2	38.6
2	48.6	32.1	49.5	21.5	38.4	38.9	50.3	28.8
3	14.5	24.9	21.6	24.5	24.4	25.7	26.8	30.7
4	6.3	2.4	6.2	6.1	1.2	0.7	6.6	1.9
5	1.9	0.5	1.0	2.0	0	0	3.1	0
Gully erosion 1961/62 (% of catchment area):								
Class 1	28.3	30.3	20.5	28.0	30.6	34.9	5.8	33.7
2	44.4	32.4	46.2	26.9	33.8	26.2	54.4	36.8
3	18.9	32.4	24.6	30.0	32.5	37.3	30.4	25.3
4	5.5	4.4	6.4	12.9	2.5	1.6	6.8	3.7
5	2.9	0.5	2.3	2.2	0.6	0	2.6	0.5
Gully erosion 1979/80 (% of catchment area):								
Class 1	24.6	35.7	34.3	31.8	19.7	32.0	5.9	26.2
2	48.3	21.2	19.9	17.0	39.5	24.2	42.1	36.7
3	16.2	31.1	29.8	35.3	33.1	38.4	40.2	31.1
4	7.0	10.4	10.5	10.2	6.3	3.1	6.9	5.5
5	3.9	1.6	5.5	5.7	1.4	2.3	4.9	0.5
Average gully erosion class:								
1950	2.0	1.9	2.2	2.0	1.9	1.9	2.4	2.0
1961/62	2.1	2.1	2.2	2.3	2.1	2.1	2.5	2.0
1979/80	2.2	2.2	2.3	2.4	2.3	2.2	2.6	2.2
Dominating class:								
1950	2	1	2	1	1/2	2	2	1
1961/62	2	1-3	2	1/3	1-3	1/3	2	1/2
1979/80	2	1/3	1	1/3	2	3	2/3	2
1983 (1)	-	-	1	2	-	-	-	-

(1) Strömquist and Larsson, 1988.

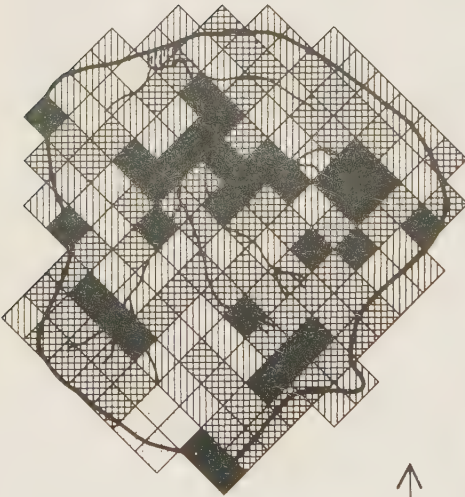
Leribe 1



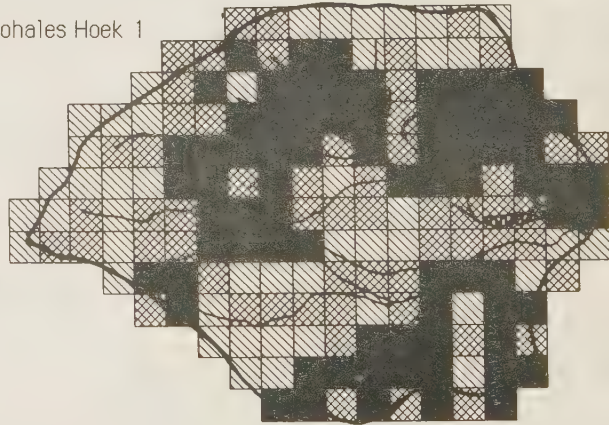
Maseru 1



Mafeteng 1



Mohaies Hoek 1



Erosion class

- 5: very severe erosion (> 50 % of the square affected)
- 4: severe erosion (25-50 % affected)
- 3: moderate erosion (obvious but < 25 % affected)
- 2: slight erosion (noticeable)
- 1: no apparent erosion

Figure 4.15. Sheet erosion according to the SARCCUS classification (see App. 2) in the catchments for which statistical analyses were carried out (i.e. Leribe 1, Maseru 1, Mafeteng 1, Mohaies Hoek 1).

Table 15. Results of the grid square inventory of gully and catchment characteristics in the four catchments of which soil maps are available, i.e. Leribe 1, Maseru 1, Mafeteng 1, and Mohales Hoek 1. The results are presented as averages of all grid squares in each catchment, and as averages of the grid squares in each catchment in which gullies were found. For some of the parameters absolute figures were used, for others classes. The dimension or number of classes is indicated in brackets in the left column and the class limits are described in detail in Appendix 2.

	Leribe 1	Maseru 1	Mafeteng 1	Mohales Hoek 1	All four catchments
All grid squares:					
Number of grid sq.	292	180	151	179	802
Gully length (m)	104	76	110	152	110
Piping (3)	0.6	0.6	0.8	1.0	0.7
Gully depth (3)	0.5	0.6	0.5	0.7	0.6
Gully heads (no.)	0.9	0.4	0.6	0.9	0.8
Erodibility (5)	3.3	2.6	3.4	3.1	3.1
Duplex soils (5)	2.5	1.8	3.6	3.2	2.7
Slope (%)	15	19	10	16	15
Landuse (5)	2.6	2.3	3.3	2.2	2.6
Sheet erosion (SARCCUS classification) (5)	3.9	3.7	3.8	4.2	3.9
Gully erosion (SARCCUS classification) (5)	2.2	2.3	2.2	2.8	2.3
Grid squares with gullies:					
Number of grid sq.	114	59	69	117	359
Gully length (m)	267	232	244	234	245
Piping (3)	1.4	1.8	1.8	1.6	1.6
Gully depth (3)	1.2	1.7	1.0	1.1	1.2
Gully heads (no.)	2.3	1.4	1.4	1.4	1.7
Erodibility (5)	3.8	3.2	4.1	3.7	3.7
Duplex soils (5)	3.7	2.8	4.7	3.8	3.8
Slope (%)	11	16	6	13	12
Landuse (5)	2.6	2.8	2.9	2.4	2.6
Sheet erosion (SARCCUS classification) (5)	4.2	3.6	4.1	4.4	4.1
Gully erosion (SARCCUS classification) (5)	3.0	3.4	2.8	3.1	3.0

The averages of gully erosion based on the SARCCUS classification differ somewhat from the gully length averages. For all grid squares, Mohales Hoek 1 has the highest average for both parameters. Maseru 1 has the second highest average of SARCCUS gully erosion but the lowest average gully length. When the grid squares with gullies are considered, the average of gully erosion according to the SARCCUS classification is highest in Maseru 1, but the gully length average is still lowest in the same catchment. This may indicate that in Maseru 1, the gullying processes tend towards widening, rather than lengthening, either through the fusion of recently initiated gully heads along the walls of the main gullies, or through regular sidewall erosion processes (e.g. undermining of the gully walls by water flow along the bottom).

4.4.3. Correlation coefficient analysis

The results of Spearman Rank correlation coefficient analyses of Leribe 1, Maseru 1, Mafeteng 1, and Mohales Hoek 1 are presented in Table 16, based on all grid squares in the catchments, and Table 17, based on grid squares where gullies are present. The parameters

listed in Table 7 are correlated with gully length, SARCCUS gully erosion, piping and sheet erosion and the relationship discussed under these headings below. When using a matrix of all grid squares in the catchments, the correlation is naturally high between the former two and the gully dependent parameters, i.e. gully heads, gully depth and piping. These three parameters were therefore only correlated with gully length and gully erosion (SARCCUS) using a matrix of grid squares with gullies. As piping is a gully related variable, the correlation analyses with other parameters (e.g. slope) were only carried out for grid squares with gullies. Sheet erosion, on the other hand, being largely unrelated to gullying, was only analysed using all grid squares, not grid squares with gullies.

It is once again worth mentioning that gully length is a measure of the total length of gullies in a grid square, while gully erosion using the SARCCUS classification is a rough measure of the lateral extent of gullies in the grid square.

Gully length

There is naturally a high correlation between gully length and gully erosion using the SARCCUS classification, when all grid squares are analysed. There is not, however, a very high correlation between gully length and gully erosion (SARCCUS) when using a matrix of grid squares with gullies (Table 17). The correlation between gully length and gully erosion (SARCCUS) decreases in all catchments if the grid squares with gullies are singled out and analysed. This indicates that a dense network of gullies (high drainage density) and laterally extensive gullying do not necessarily coincide, which shows that both types of measure should be analysed and used when characterizing the severity and extent of gully erosion in a catchment. The correlation is highest in Leribe 1 and Mafeteng 1. This may indicate that sidewall processes and lateral fusion of small gullies extending from the main gullies are at work simultaneously with lengthening and headward cutting, more so in these two catchments than in Maseru 1 and Mohales Hoek 1.

The correlation between gully length and soil erodibility is highest in Mohales Hoek 1 and lowest in Maseru 1 when using a matrix of all grid squares, which indicates that gully erosion is slightly more confined to erodible soils in the former catchment. Maseru 1 has the lowest average erodibility of the four analysed catchments (Table 15), and the existing and recently initiated gullies are to some degree bound to develop further in low erodibility soils as the heads migrate upslope, hence the low correlation between erodibility and gully length. When the analysis was carried out for grid squares with gullies the correlation with erodibility decreased sharply in Leribe 1 and Mafeteng 1, and slightly in Mohales Hoek 1. This is partly the result of an overall increase in average erodibility in the two catchments, as the grid squares with gullies are singled out, i.e. the difference in ranking of the erodibility grid squares is smaller. In Maseru 1 it remained constant (relatively low).

When using all grid squares, there is a relatively high correlation with the distribution of duplex soils in the catchments. Although the difference between the catchments is small, the coefficient is slightly higher in Maseru 1 and Mafeteng 1. However, the coefficient is not particularly high in any of the catchments, indicating that gully erosion is not solely confined to duplex soils. The non-perfect correlation is caused both by gullies eroding in non-duplex soils, and by grid squares with duplex soils but no gully erosion. When only the grid squares with gullies are analysed there is a sharp decrease in correlation. As the average extent of duplex soils in the grid squares increases during this procedure, the decrease in correlation is the result of an increased number of grid squares of a high class, i.e. the difference in ranking is low.

The correlation with slope is negative in all catchments, supporting the view that gully erosion is not dependent on steep slopes, rather the opposite. The correlation is low, however, since some of the gullies have extended upslope and reach closer to the escarpment or water divide, and consequently steeper terrain. When the matrix of grid squares with gullies is used the correlation is increased (but still negative) in Leribe 1 and Maseru 1, but decreased in Mafeteng 1 and Mohales Hoek 1. This would indicate that gully development, where gullies are present, has been more confined to lower slopes in the former two catchments, than in Mafeteng 1 and Mohales Hoek 1.

The correlation with landuse is very low in all four catchments. However, this reflects the fact that most gullies develop in the central parts of the catchments, which are almost entirely used for cultivation, rather than a low correlation with landuse. The grid squares in the centre of the catchments where gullying is evident, all belong to the same class (3), and

consequently the ranking procedure of the method used is ineffective and the correlation low. The correlation is higher for Maseru 1 and Mhales Hoek 1, indicating that the influence of landuse, whether high or low, is slightly larger in these two catchments.

The correlation with sheet erosion is generally low, being slightly higher in Mafeteng 1 and Mhales Hoek 1. In other words, severe sheet erosion is more often found in gullied areas in these two catchments than in Leribe 1 and Maseru 1. This reflects the prominence of shallow piping in Mafeteng 1 and Mhales Hoek 1, creating, together with sheet erosion, vast badland areas. When using the matrix of grid squares with gullies the correlation is highest (albeit low) in Mafeteng 1, indicating that the severity of gullying and sheet erosion tend to increase together in this catchment. This, again reflects the extensive badland areas in the catchment. The low correlation between gully length and sheet erosion does not mean that the latter does not influence the former. Sheet erosion on the escarpment and colluvial slopes in the catchments increases the velocity and amount of runoff further downslope. This increases the potential for gullying through surface runoff or piping further downslope, the latter since more water is available for infiltration.

The correlation with piping, when the grid squares with gullies are analysed, is highest in Mafeteng 1, followed by Leribe 1. A high correlation indicates that piping, where present, frequently causes the development of a dense network of gullies. As the deep kind of piping dominates in Leribe 1 and the shallow kind in Mafeteng 1, the statement appears to apply to both types of piping. But the deep kind is more dependent on an outlet to develop, i.e. an exposed gully wall, than the shallow kind. In Leribe 1, therefore, piping is accentuated (favoured) by long stretches of deep gullies, hence the high correlation. The pipes then develop into new gullies, creating more potential piping sites. In Mafeteng 1 the high degree of piping is the cause of the extension and fusion of discontinuous gullies that, due to shallow piping in the badland areas, have developed in cracks and fissures in the B-horizon. The shallow type of piping is less dependent on long stretches of deep gullies for initiation. In both cases, however, the two processes (piping and gully extension) are clearly interrelated and tend to accelerate each other.

The correlation between gully length and depth (grid squares with gullies)(Table 17) is highest in Leribe 1 and lowest in Mhales Hoek 1. A high correlation indicates that large depths are found where the drainage network is dense. In Leribe 1 the high correlation may be related to the requirements and effects of deep piping discussed above, i.e. deep piping cannot develop unless a sufficiently deep gully is present (below or at the critical horizon). Once the main gully has eroded to this depth, the deep piping is accelerated and more deep gullies develop, creating a dense network of gullies. The same is valid in Maseru 1 which also has a high degree of deep piping. In Mhales Hoek 1 there is less deep piping that causes gullying, hence the correlation is lower. The high correlation in Mafeteng 1 may be explained by the fact that the Spearman correlation analysis ranks the two variables from high to low and then compares the rankings. The average depth in Mafeteng is the lowest of all four catchments, hence the gully network may be denser at the largest depths found in the catchment, although the depths are small compared to Leribe 1 and Maseru 1. Also, a very dense network of gullies is found in the east of Mafeteng 1 where both deep and shallow piping occurs. This relatively large area, covering several grid squares, may have had a significant influence on the correlation between gully length and depth in this particular catchment.

The correlation between gully length and number of gully heads (grid squares with gullies)(Table 17) is not very high in any of the catchments. This would indicate that a dense network of gullies is not necessarily connected with a high number of gully heads. On the contrary, a high drainage density in a grid square is usually not related with discontinuous gullies or a large number of gully heads, instead the gullies run right through the square. A high number of gully heads is found in the outskirts of the gully system, and in the form of recently initiated, short tributaries along the main gullies. The correlation is highest in Leribe 1 reflecting the high number of tributaries that have developed below the western and eastern escarpments (see Fig. 4.1).

Table 16. Results of the Spearman Rank correlation coefficient analyses of grid square parameters in Leribe 1, Maseru 1, Mafeteng 1, and Mohales Hoek 1, using a matrix of all grid squares in the catchments. Where not otherwise indicated, the significance level is 99.9 %. * indicates a significance level of 99 % and ** a level of 95 %. A level < 95 % was considered insignificant and the result is presented in brackets. A value of ± 1 is a perfect correlation and 0 a total absence of correlation.

	Leribe 1	Maseru 1	Mafeteng 1	Mohales Hoek 1	All four catchments
Number of cases	292	180	151	171	802
Correlation with gully length:					
Soil erodibility	0.47	0.39	0.50	0.59	0.49
Duplex soils	0.56	0.61	0.59	0.56	0.57
Slope	-0.25	-0.20	-0.23	-0.27	-0.25
Landuse	(0.01)	0.37	(-0.09)	0.32	0.12*
Sheet erosion (SARCCUS classif.)	0.18*	(-0.07)	0.35	0.35	0.22
Gully erosion (SARCCUS classif.)	0.72	0.66	0.67	0.56	0.68
Correlation with gully erosion (SARCCUS classification):					
Soil erodibility	0.36	0.48	0.46	0.40	0.40
Duplex soils	0.56	0.70	0.59	0.39	0.52
Slope	-0.20	(-0.12)	-0.24*	-0.34	-0.21
Landuse	(0.10)	0.38	(0.00)	0.27	0.14
Sheet erosion (SARCCUS classif.)	0.29	(-0.08)	0.32	0.35	0.23
Correlation with piping:					
Sheet erosion (SARCCUS classif.)	0.20	(-0.06)	0.36	0.31	0.22
Correlation with sheet erosion (SARCCUS classification):					
Soil erodibility	(-0.03)	-0.44	(0.10)	0.34	(0.02)
Duplex soils	(0.09)	-0.15**	0.18**	0.40	0.13
Slope	0.31	0.46	(0.07)	-0.20*	0.18
Landuse	(-0.08)	-0.45	(-0.05)	(0.13)	-0.13
Gully depth	0.18*	(-0.01)	0.30	0.30	0.18
Gully heads	0.22	(-0.08)	0.20**	0.20*	0.17

Gully erosion (SARCCUS classification)

The correlation between gully length and gully erosion (SARCCUS classification) has already been discussed. The correlation between gully erosion (SARCCUS classification) and the other 8 parameters is frequently of the same magnitude as and sometimes practically identical to the corresponding correlation with gully length. A few deviations from this pattern are worth mentioning.

In all catchments except Maseru 1, soil erodibility has a higher correlation with gully length than with gully erosion (SARCCUS classification) when using all grid squares. As Maseru 1 has the lowest average soil erodibility and gully length, this indicates that lengthening rather than widening occurs in areas with more erodible soils in this catchment.

The correlation with duplex soils is considerably lower for gully erosion (SARCCUS classification) compared to gully length in Mohales Hoek 1. This would indicate that gullies in this catchment are long rather than wide where duplex soils are present. In Maseru 1 the correlation is higher for gully erosion (SARCCUS classification), suggesting that gullies in this catchment widen rather than extend in duplex soil areas.

Table 17. Results of the Spearman Rank correlation coefficient analyses of grid square parameters in Leribe 1, Maseru 1, Mafeteng 1, and Mohales Hoek 1, using a matrix of grid squares where gullies are found. Where not otherwise indicated, the significance level is 99.9 %. * indicates a significance level of 99 % and ** a level of 95 %. A level < 95 % was considered insignificant and the result is presented in brackets. A value of ± 1 indicates a perfect correlation and 0 a total absence of correlation.

	Leribe 1	Maseru 1	Mafeteng 1	Mohales Hoek 1	All four catchments
Number of cases	114	59	69	117	359
Correlation with gully length:					
Soil erodibility	(0.09)	0.38*	(-0.01)	0.38	0.21
Duplex soils	(0.05)	(0.24)	(0.11)	0.34	0.17*
Slope	-0.26*	-0.40*	(-0.01)	(-0.17)	-0.21*
Landuse	(-0.02)	(0.14)	(0.16)	(0.18)	(0.09)
Piping	0.43	0.37*	0.56	0.41	0.43
Gully depth	0.60	0.58	0.59	0.47	0.54
Gully heads	0.47	0.29**	0.29**	0.33	0.36
Sheet erosion (SARCCUS classif.)	(0.02)	(0.01)	0.31**	(0.11)	(0.10)
Gully erosion (SARCCUS classif.)	0.63	0.45	0.59	0.33	0.50
Correlation with gully erosion (SARCCUS classification):					
Soil erodibility	(-0.03)	0.56	(0.12)	(0.17)	0.11**
Duplex soils	(0.02)	0.43*	(0.11)	0.19**	(0.05)
Slope	-0.36	-0.52	(-0.04)	-0.27*	-0.24
Landuse	(0.15)	0.44*	0.26**	(0.17)	0.20
Piping	0.35	0.31**	0.44	0.24**	0.34
Gully depth	0.49	0.34**	0.38*	0.33	0.45
Gully heads	0.24**	(-0.12)	(-0.02)	(-0.09)	(0.02)
Sheet erosion (SARCCUS classif.)	(0.05)	(-0.07)	0.28**	0.21**	(0.08)
Correlation with piping:					
Soil erodibility	(-0.06)	0.33**	(-0.13)	(0.13)	(0.04)
Duplex soils	0.25*	0.29**	(0.10)	(0.10)	0.16*
Slope	-0.23**	(-0.23)	(-0.13)	-0.32	-0.25
Landuse	(0.11)	(0.22)	0.32**	0.21**	0.21
Gully depth	0.60	0.30**	0.44	0.23**	0.40
Gully heads	(0.14)	(-0.13)	0.31**	(0.03)	(0.05)

The correlation with piping (using the matrix of grid squares with gullies) is lower for gully erosion (SARCCUS classification) than for gully length, indicating that where piping is present, the gullies tend to lengthen rather than widen.

The correlation with gully depth is also lower for gully erosion (SARCCUS classification) than for gully length (grid squares with gullies), indicating that the gullies are more laterally spread out where the depths are smaller. This is, for example, the case where a gully has cut down to the resistant bedrock surface. The water flowing along the bottom is not loaded with sediment and the bedrock surface is smooth. Hence, the velocity and erosivity of the turbulent flow is high. Downward scouring is restricted but widening occurs.

Piping

The correlation between piping and gully length and gully erosion (SARCCUS classification) has already been discussed. The analyses of correlation with all other parameters except sheet erosion were carried out only for grid squares where gullies are present (Table 17), since piping always occurs in conjunction with gullies.

The correlation between piping and soil erodibility is very low, being slightly higher in Maseru 1 than in the other catchments. The results also have a low significance level and the only conclusion that can be drawn is that soil erodibility does not influence the degree of piping. The slightly higher value in Maseru 1 would indicate that piping is more common in areas where erodibility is comparatively high in this catchment. The other catchments have a negative correlation indicating the opposite relationship but, as mentioned, the values are not within a reasonable significance level.

There is a low correlation between piping and duplex soils. This fact supports the view that piping may occur in non-duplex soils, in other words, duplex properties of a soil are not prerequisites for piping to occur.

There is also a low (insignificant) correlation between piping and landuse, indicating that landuse does not directly affect the degree of piping. Indirectly, however, the effects of landuse on sheet and gully erosion may affect piping in an area.

There is a relatively high correlation between piping and gully depth in Leribe 1 and Mafeteng 1. The high correlation in Leribe 1 is due to the dominance of the deep kind of piping over the shallow type, and the former is dependent on deep, exposed gully walls to develop. In other words, the deep piping in Leribe 1 cannot develop unless deep gullies exist. As a consequence of the deep piping, more deep gullies develop. In Mafeteng 1 the high correlation is probably largely the result of the grid squares covering the dense and deep gully network in the eastern part of the catchment. Piping in this area is extensive (see Fig. 4.5) and present along almost all gullies. Most of the gullies in the area have developed through a combination of deep and shallow piping. This is also where the largest depths in the catchment are found.

There is a low correlation between piping and number of gully heads in all catchments. It is considerably higher in Mafeteng 1 compared to the other catchments. The high correlation is the result of the extensive piping and reflects the fact that the process ultimately leads to gully head initiation as the pipe roof collapses. Frequently, the collapse is discontinuous along the pipe and consequently there is a higher number of gully heads before the discontinuous gullies fuse together.

The correlation between piping and sheet erosion is low (Table 16). There is a higher correlation between piping and sheet erosion (for all grid squares) in Mafeteng 1 and Mohales Hoek 1 compared to Leribe 1 and Maseru 1. This is due to the high degree of shallow piping in the former two catchments. Shallow piping and sheet erosion often occur together and tend to accelerate gully development. This is the case in Mafeteng 1 and Mohales Hoek 1. In the latter in particular, it appears as if the extensive piping has, in combination with sheet erosion, caused the gully heads to fuse together laterally (sideways) to form vast badland areas.

Sheet erosion (SARCCUS classification)

The correlation between sheet erosion and gully length, gully erosion (SARCCUS classification) and piping has already been discussed. As sheet erosion is not a gully related variable, the correlation was only analysed using a matrix of all grid squares in each catchment.

The correlation between sheet erosion and the other 6 parameters is very low or insignificant in most cases, indicating that the parameters frequently appear to be independent of sheet erosion, and vice versa. Some of the higher correlations are worth mentioning.

There is a high negative correlation between sheet erosion and erodibility in Maseru 1. However, the result only reflects the fact that sheet erosion is more extensive on the escarpment in this catchment (in the form of rock stripping) than in the flatter parts where erodible soils are found. Hence, the result should not be seen as an indication that sheet erosion is less on erodible soils.

One of the better correlations is with duplex soils in Mohales Hoek 1. However, the result reflects the presence of sheet erosion in the flatter and cultivated parts of the catchment,

where duplex soils are found, rather than a relationship between sheet erosion and duplex soils.

This is also reflected in the correlation between sheet erosion and slope in Maseru 1. It is relatively high and positive, indicating an increase in sheet erosion as slope increases. As mentioned above, sheet erosion is very extensive on the escarpment in this catchment, which is where the steepest slopes are found. The same condition is also found in Leribe 1. The reverse is true in Mohales Hoek 1. The correlation is low but negative, indicating that sheet erosion is more prominent in the flatter part of this catchment. The sheet erosion in the catchments is shown in Figure 4.15.

4.5 Rainfall analysis

This section first provides a general characterization of the monthly and annual rainfall at the four different meteorological stations used in this study; secondly, some tentative results of the analyses of monthly and annual rainfall trends; and thirdly, analyses of the monthly and annual rainfall records at the four stations to detect the possible effects of antecedent rainfall conditions on gully erosion, i.e. potentially erosive dry-wet sequels.

4.5.1 Annual and monthly rainfall characteristics

The mean monthly and annual rainfall figures for the four meteorological stations are provided in Table 18, together with the coefficient of variation and the maximum and minimum amounts of rainfall recorded. The monthly rainfall and variation are also shown in Figure 3.10.

The meteorological station in Maseru receives the lowest annual rainfall of the four stations (average 684 mm), followed by Mohales Hoek (727 mm) and Mafeteng (705 mm). Leribe has the highest annual rainfall (785 mm). Leribe and Maseru receive a slightly larger portion of their annual rainfall (87 %) during the wet season (October-April), compared to Mafeteng (86 %) and Mohales Hoek (85 %). The difference (range) in mean monthly rainfall between the four stations is smallest in March through October (3-9 mm). The difference (range) is larger in November through February (11-24 mm). The highest monthly rainfall from September through March is found in Leribe, in April in Mafeteng, and in May-August in Mohales Hoek. The lowest rainfall in November-January is found in Mafeteng, in February-June in Maseru, in April also in Leribe, in July in Leribe, in August-September in Maseru, and in October in Maseru and Mafeteng.

The largest coefficient of variation of annual rainfall is found in Leribe (24 %), followed by Mafeteng (23 %) and Maseru (22 %). Mohales Hoek has the lowest variation (21 %). The coefficient for monthly rainfall increases, as expected, as the mean monthly rainfall decreases during the year, and is highest in June through September for all four stations. There is a sharp increase in variation from April to May, and a very sharp decrease from September to October, i.e. the beginning of the dry and wet season respectively. Although the difference (range) in coefficient of variation between the stations is not large during the months of the wet season (3-15 units) the coefficient is slightly higher in October in Mafeteng and Mohales Hoek, in November in Leribe and Maseru, in December in Mafeteng, in January-February in Mohales Hoek, in March in Mafeteng, and in April in Mohales Hoek. The coefficient is lowest in October in Maseru, in November in Mohales Hoek, in December-March in Leribe, and in April in Leribe and Mafeteng. During the dry season (May-September) the coefficient of variation is highest in May-July in Leribe, in May also in Mafeteng and Mohales Hoek, and in August-September in Mafeteng. The coefficient is lowest in May in Maseru, in June-August in Mohales Hoek, and in September in Leribe.

For the individual stations, during the wet season (Oct.-April), the coefficient of variation of monthly rainfall is highest in April and lowest in February-March in Leribe. For Maseru it is highest in April and lowest in February. For Mafeteng it is highest in October and lowest in November and February, and for Mohales Hoek it is highest in April and lowest in March.

A high rainfall variability in October-December may prove critical as far as soil erosion is concerned. After the dry season and during ploughing and planting, before the crops have started to grow, vegetation is sparse and the soil vulnerable to erosion. Low rainfall during this period will delay seed germination and vegetative development. High rainfall may cause severe erosion, especially if preceded by a period of drought.

Table 18. Mean annual and monthly rainfall, standard deviation, coefficient of variation, and maximum and minimum rainfall recorded for the meteorological stations in Leribe, Maseru, Mafeteng and Mochales Hoek. Calculations of data from Hydrological Survey (1970, 1988).

	Leribe	Maseru	Mafeteng	Mochales Hoek
Annual: No. of cases	59	64	62	63
Mean rainfall (mm)	785	684	705	727
Standard deviation	190	151	164	156
Coeff. of variation (%)	24	22	23	21
Rainfall during wet season (Oct.-Apr.) (%)	87	87	86	85
Max (mm)	1290	1119	1056	1142
Min (mm)	408	419	353	408
January: No. of cases	64	65	66	67
Mean rainfall (mm)	126	110	104	107
Standard deviation	64	63	62	66
Coeff. of variation (%)	51	58	59	61
Max (mm)	331	330	278	304
Min (mm)	25	17	8	27
February: No. of cases	64	65	67	66
Mean rainfall (mm)	111	95	103	103
Standard deviation	55	50	58	58
Coeff. of variation (%)	50	52	56	59
Max (mm)	252	249	316	275
Min (mm)	22	7	0	10
March: No. of cases	64	65	65	67
Mean rainfall (mm)	104	95	103	102
Standard deviation	52	51	67	52
Coeff. of variation (%)	50	54	65	52
Max (mm)	251	218	298	240
Min (mm)	12	13	10	7
April: No. of cases	64	65	65	67
Mean rainfall (mm)	58	58	64	61
Standard deviation	39	40	43	42
Coeff. of variation (%)	67	68	67	70
Max (mm)	190	161	179	172
Min (mm)	0	0	0	0
May: No. of cases	64	65	66	67
Mean rainfall (mm)	30	27	29	32
Standard deviation	28	23	27	29
Coeff. of variation (%)	91	87	91	91
Max (mm)	112	85	113	147
Min (mm)	0	0	0	0
June: No. of cases	64	65	65	67
Mean rainfall (mm)	13	11	13	14
Standard deviation	19	15	16	15
Coeff. of variation (%)	154	132	130	107
Max (mm)	77	56	75	56
Min (mm)	0	0	0	0

Table 18. Continued.

	Leribe	Maseru	Mafeteng	Mohales Hoek
July: No. of cases	63	65	67	66
Mean rainfall (mm)	11	12	12	14
Standard deviation	18	17	18	19
Coeff. of variation (%)	165	143	147	135
Max (mm)	92	87	82	68
Min (mm)	0	0	0	0
August: No. of cases	61	65	66	65
Mean rainfall (mm)	15	14	18	20
Standard deviation	21	20	27	26
Coeff. of variation (%)	138	144	150	132
Max (mm)	80	90	166	97
Min (mm)	0	0	0	0
September: No. of cases	62	65	66	66
Mean rainfall (mm)	31	24	27	28
Standard deviation	38	31	36	37
Coeff. of variation (%)	122	129	133	131
Max (mm)	173	154	156	162
Min (mm)	0	0	0	0
October: No. of cases	63	64	65	67
Mean rainfall (mm)	71	62	62	66
Standard deviation	43	36	43	45
Coeff. of variation (%)	60	58	70	68
Max (mm)	232	138	208	186
Min (mm)	8	2	0	0
November: No. of cases	63	64	66	67
Mean rainfall (mm)	100	88	81	83
Standard deviation	58	50	45	46
Coeff. of variation (%)	59	57	56	55
Max (mm)	306	222	195	216
Min (mm)	2	2	4	0
December: No. of cases	63	64	66	66
Mean rainfall (mm)	110	87	86	97
Standard deviation	57	48	53	55
Coeff. of variation (%)	52	55	62	56
Max (mm)	271	194	272	216
Min (mm)	20	5	8	9

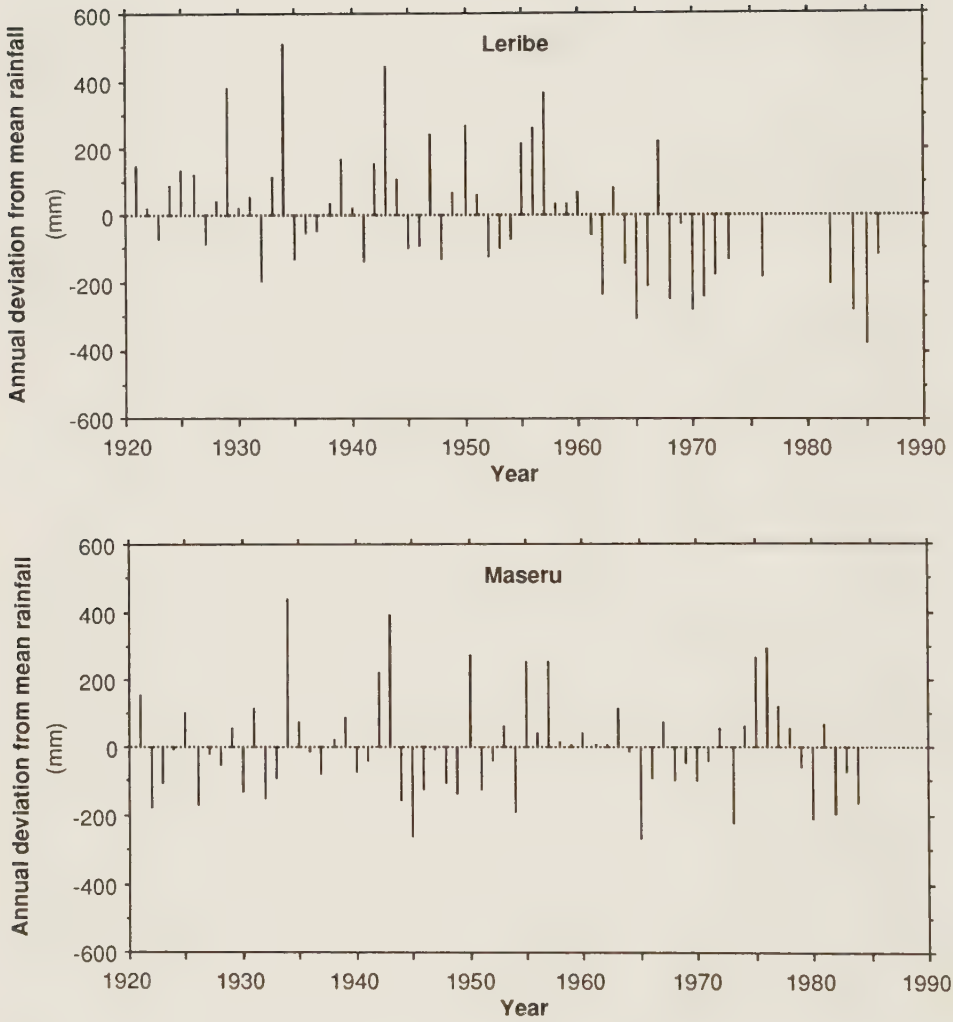


Figure 4.16. Annual deviations from mean rainfall 1921-1987 at the meteorological stations in Leribe, Maseru, Mafeteng and Mochales Hoek (sources: Hydrol. Survey, 1970, 1988).

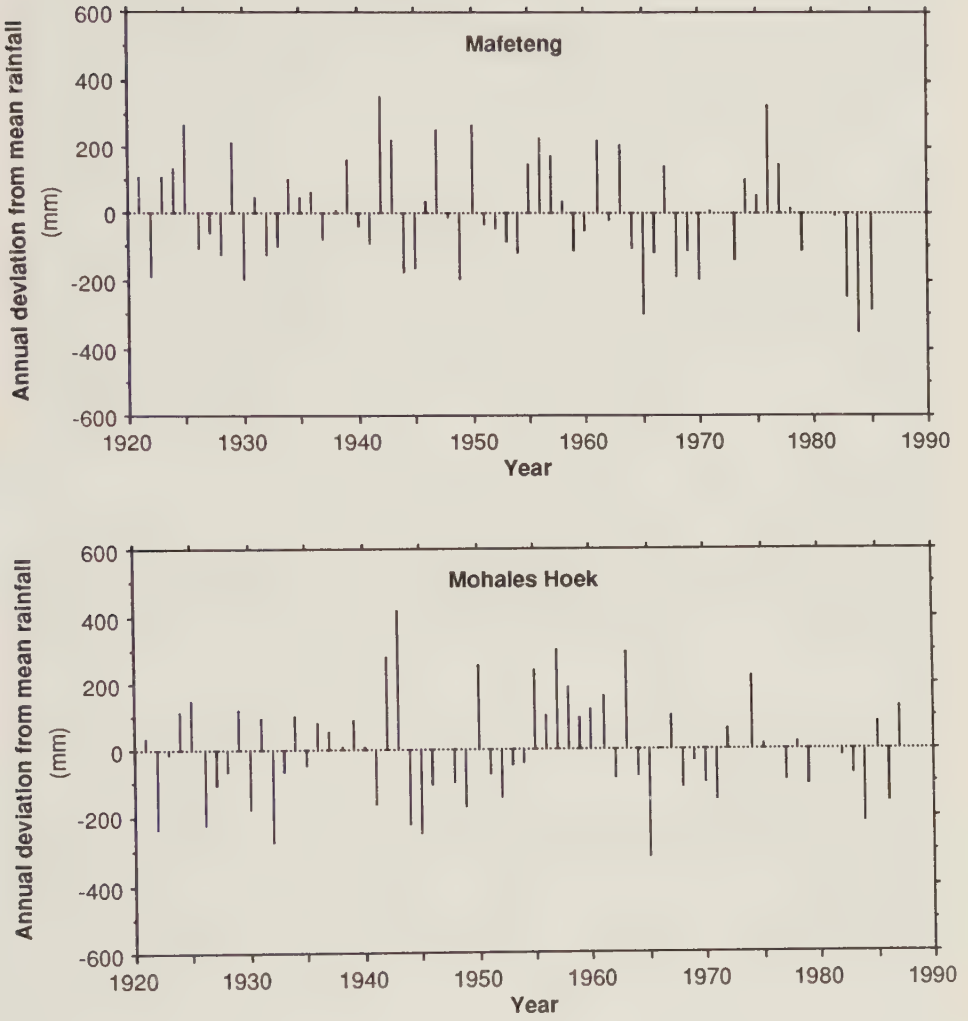


Figure 4.16. Continued.

4.5.2 Antecedent moisture conditions - analysis of annual and monthly rainfall records

The effects of antecedent rainfall on gully erosion, and of large discrepancies within a dry or wet spell, have been mentioned earlier (Section 2.4.2, 3.1.2). Most important are the effects of antecedent moisture on vegetation, as the protective cover is reduced during a dry spell. On cultivated fields the months of October and November are crucial, since the fields are unprotected and very vulnerable to erosion during ploughing and planting. Another critical period is after the stubble (maize or sorghum) has been removed from the fields in May-June, through grazing or to be used for fuel, and the soil is left bare. High rainfall in June-September may prove devastating, especially since the grazed areas also have a poor vegetation cover during this period due to the dry weather.

One example, often referred to in the literature as having caused severe soil erosion in Lesotho is the wet year of 1934 that followed the drought of 1932-33 (e.g. Pim, 1935). This sequence was more or less pronounced at the four stations used in this study. Similar trends can be followed on several occasions in the records. The detailed analyses of the annual and monthly rainfall records were carried out for the period 1950 to 1980, which is the period for which gully erosion analyses have been carried out. Since the air photos on which the gully erosion analyses are based were taken in April-May, the first period analysed lasts from April 1950 through May 1961 while the second period lasts from June 1961 to April 1980. The results are presented as direct comparisons between the four meteorological stations. It is not possible to determine whether or not erosion actually occurred during these dry-wet sequels (annually or monthly), but the events presented have been classified as potentially very erosive.

Annual rainfall

The deviations from the mean annual rainfall at the four meteorological stations between 1921 and 1987 are shown in Figure 4.16. The first period under examination (1950-1961) experienced a dry spell roughly from 1951 through 1954. This drought was less pronounced in Maseru, which had above normal rainfall in 1952. The drought was followed by a series of 3-4 wet to very wet years. Again this was less pronounced in Maseru. The remaining part of the period through 1961 was wet in Mhales Hoek, and normal in Leribe and Maseru. Mafeteng experienced a drought during 1959 and 1960, and a very wet 1961.

The second period (1962-80) was in Leribe characterized by a series of dry to extremely dry years from 1962 through 1973, except for 1963, which was about normal, and 1967, which was wet. Due to the discontinuous record of monthly rainfall from 1975 and onwards for the Leribe station, most of the annual rainfall figures for the later part of the 70s are missing. 1976 was very dry however.

The station in Maseru experienced an extremely dry 1965 and a dry 1966, followed by above normal rainfall in 1967. 1973 was also extremely dry and was followed by above normal rainfall in 1974, and very high rainfall in 1975-76.

The annual rainfall records for the stations in Mafeteng and Mhales Hoek are almost identical. Mafeteng had a more pronounced drought in 1964-66, and a normal year in 1975. Mhales Hoek had very high rainfall in 1963, and a wet 1974. Annual rainfall figures are missing for Mhales Hoek for 1976 and 1980.

Monthly rainfall

Prolonged rains and a continuously rainy wet season cause the clays to rehydrate and close the cracks in the top soil, thus reducing the infiltration rate (Baillie et al., 1986). The effect of a dry period during the wet season is therefore that cracks and fissures in the clayey B-horizon of the duplex soils may open up and widen, creating potential piping sites for the next rainfall. Similarly, a wet period during the dry season, or a very wet period at the beginning of the wet season may cause severe piping as the cracks and fissures are open. This was noted by Baillie et al. (1986) in Tunisia. Changes in vegetation cover during the dry periods accentuate the problem. A crucial sequence of monthly rainfall, as far as soil erosion is concerned, is therefore when a number of months with well below normal rainfall are followed by a very wet period. Another potentially erosive event is when a month during the dry

season, or at the beginning of the wet season, experiences unusually high rainfall. The effect of the wet spell is dependent on the severity and length of the drought and on how pronounced the wet spell is.

It is not possible to show diagrams of the monthly deviations from mean at the four stations, such figures are too space-consuming. Instead, Table 19 is a summary and presents the dry-wet sequels, that may have caused very severe erosion, in order of appearance from 1950 to 1980. The four stations are compared simultaneously as to whether or not the dry-wet sequel occurred, and how pronounced it was. It should be noted that these sequels are extreme events and that erosion is in no way confined to these events exclusively. On the contrary, erosive rainfall conditions occur frequently during the wet season. One extreme rainfall event, that does not show on the monthly rainfall record, may have initiated a gully. Less erosive rains, that perhaps would not have been capable of doing so, may then be responsible for further development. Table 19 is summarized below for each station.

Leribe

Four potentially erosive dry-wet sequels occurred during the first period (1950-1961). One of these appears to have been very severe, the drought starting in October 1954 and ending with excessive rainfall in January 1955. In addition, July 1959 was very wet. In an analysis of the annual rainfall record and deviations from mean alone, and not the monthly rainfall deviations, the three less severe sequels and the wet month of July would not have appeared. It is therefore quite obvious that a more detailed analysis than of annual rainfall is necessary, the minimum seeming to be on a monthly basis.

During the second period (end of 1961 to 1980) seven dry-wet sequels occurred. The two most severe appear to have occurred from October 1965 through January 1966, and the same months in 1966/67. The former sequel does not show in the annual record but the latter coincides with the end of a dry period that also appears in the annual rainfall record. The other 6 potentially erosive monthly sequels are less pronounced and do not show on an annual analysis. During the second period, Leribe also experienced an extremely wet November in 1974 that may have caused erosion.

The other stations experienced two potentially erosive sequels between 1974 and 1980. They do not appear in the Leribe records due to lack of data, but it is possible that they also occurred there.

Maseru

During the first period, 6 dry-wet sequels occurred that may have caused erosion. The most pronounced was the one from November 1951 to January 1952. In addition, September 1957 was extremely wet and July 1959 very wet. Only the sequel from December 1954 through January 1955 appears in an annual analysis. During the second period, 11 sequels occurred. The one from October 1965 through January 1966, the one from December 1972 through February 1973, and the one from October 1973 ending in heavy rainfall in January 1974, appear to have been very severe. In the analysis of the annual rainfall record, 1973 was extremely dry and 1974 had slightly above normal rainfall. None of the other sequels show in the annual rainfall records. So, once again, an analysis only of the annual rainfall record would not have been sufficient. Also, during the second period, Maseru received well above normal rainfall in September 1977.

Mafeteng

Eight dry-wet sequels, more or less pronounced, occurred during the first period. The most extreme appears to have been the one from November 1960 through March 1961. This also appears in the annual analysis, but less pronounced. The sequel from October 1954 through January 1955 also shows up in the annual analyses. None of the less pronounced sequels appear in the annual rainfall record. In addition, Mafeteng experienced an extremely wet September 1957, and a very wet July 1959 and August 1960 that may have caused severe erosion. During the second period, eight sequels occurred, the most pronounced from December 1963 through March 1964, and from October 1965 through January 1966.

The former is indicated in the annual rainfall record as a very wet 1964, the latter sequel does not show on the analysis of annual rainfall. The rainfall in March of 1968 was normal but may have caused erosion due to the three extremely dry preceding months. During the second period, Mafeteng also had an extremely wet September 1977.

Mohales Hoek

Two dry-wet sequels occurred during the first period, the most severe from October 1952 through 1953, of which there is no evidence in an annual analysis. In addition, Mohales Hoek received well above normal rainfall in July 1959 and in August 1960. Eight dry-wet sequels occurred during the second period. Three of them are more extreme: from September through November 1961, from October 1965 through January 1966, and from November 1967 through March 1968. The one in 1965/66 appears in the annual record as an extremely dry 1965 and a normal 1966. None of the other two show. Of the less severe sequels, the wet month of February 1974 appears in the annual analysis as a very wet 1974. In addition November 1963 was extremely wet, and September 1977 very wet.

Table 19. List of the occurrence of dry-wet sequels (monthly basis), and months with well above normal rainfall, at the meteorological stations in Leribe, Maseru, Mafeteng and Mohales Hoek between 1950 and 1980. The events may possibly have caused very severe erosion. The monthly rainfall rankings are: -/+ = dry/wet, -/+ = very dry/very wet, ---/+++ = extremely dry/extremely wet, where no sign is shown the rainfall was about normal (analysis of data from Hydrological Survey, 1970, 1988).

	Leribe	Maseru	Mafeteng	Mohales Hoek
November 1951	--	--	--	
December	--	--	--	
January 1952	+	++	-	
February			+	
October 1952			-	-
November			-	-
December			-	--
January 1953	---	--	--	--
February	++	+	++	++
December 1953			-	
January 1954			-	
February			-	
March			+++	
October 1954	--		--	
November	-		-	
December	--	-	+	
January 1955	+++	+++	+++	
January 1956		-	---	---
February		++	+++	+++
September 1957		+++	+++	
January 1959	-	-	--	
February	---	--	-	
March	---	-	--	
April	+	+	+	

Table 19. Continued.

	Leribe	Maseru	Mafeteng	Mohales Hoek
July 1959	++	++	++	++
September 1959			-	
October			-	
November			-	
December			++	
August 1960			++	++
November 1960			-	
December			-	
January 1961		-	--	
February		-	-	
March		+	+++	
September 1961		-	-	-
October	---	--	---	---
November	+	+	+++	+++
August 1962		-	-	-
September		-	-	-
October		-	-	--
November		++	+++	++
February 1963				---
March				++
October 1963		-		
November		+++	+++	+++
December 1963			-	-
January 1964	---	-	---	---
February	--	--	--	-
March	+	-	++	+
April		+		
January 1965			-	
February			---	
March			---	
April			+	
October 1965	--	--	--	---
November	-	-	-	-
December	--	---	---	--
January 1966	+	++	+++	+++
October 1966	-			
November	-			
December	-			
January 1967	+++			

Table 19. Continued.

	Leribe	Maseru	Mafeteng	Mohales Hoek
November 1967				—
December			---	---
January 1968	---		---	---
February	---	---	---	---
March	+	+		++
January 1969		---	---	
February		-	+	
March		+++		
December 1972	---	---		
January 1973	---	---		
February	+	++		
October 1973	-	-		
November	-	-		
December	-	-		(1)
January 1974	+	+++		-
February				+++
October 1974		-		
November	+++	+++		
September 1977	(1)	++	+++	++
October 1978	(1)	-	-	
November	(1)	-	-	-
December	(1)	+++	+	+++
Total number of erosive events:				
1950-May 1961 (2)	5	8	11	4
June 1961-1980	8	12	10	10
1950-1980	13	20	21	14

(1) Data missing.

(2) Since the air photos on which the gully erosion analyses are based were taken in May 1961, the rainfall analyses up to this month are included in the first period.

4.5.3 Rainfall trends

Figure 4.17 shows the 10-year average annual rainfall since 1921 and the linear trend for the four meteorological stations. Table 20 provides the slope coefficients and R^2 -values of the regression lines for annual and monthly rainfall (10-year averages). Looking at Figure 4.17, the 16-20 year oscillation between wet and dry spells, suggested by Tyson and Dyer (1975), appears to apply, more or less pronounced, to all four stations. Roughly the wet spells occurred at the beginning of the 1900s, 20s, 40s, 60s and 80s, and the dry spells in the early years of 1910s, 30s, 50s and 70s.

Concerning the rainfall trends, based on 10-year averages since 1921 (Table 20), it is noticeable that the annual rainfall at the stations in Leribe and Mafeteng shows a significantly negative trend, i.e. a decrease in rainfall. This trend is, by far, most pronounced in Leribe. The steep slope of the regression line for that station is to some extent influenced by the great lack of rainfall records since 1974, which is the result of one or more missing monthly value during the years. The annual rainfall figures available in the 70s are all below normal and hence the 10-year averages are low. If the linear trend for the station is calculated for the period 1921 to 1974 instead, the slope of the regression line is nevertheless steeply

negative (-3.926 mm/year). For the rainfall trends of the separate months the shortage of data is not as severe since the month for which data is missing varies from year to year, i.e. the records are more continuous than for annual rainfall.

The trends for each month and station vary, as do the coefficient of explanation and significance level. The former is generally below 50 %. For the station in Leribe statistically significant negative trends were found in January through March, June through August, and October through December, and a positive trend in August. For the station in Maseru a negative trend was found in March, and positive trends in August and September. For Mafeteng negative trends were found in March, May and December, and a positive trend in April. For Mhales Hoek negative trends were found in March, and May, and positive trends in April, September and October. The largest negative monthly trend for all stations, within a reasonable significance level, was found in November in Leribe. The largest positive trend was found in September in Maseru and April in Mhales Hoek.

Areas with a rainfall that, in a normal year, is barely sufficient for good agricultural production and vegetation cover are balancing close to the edge of catastrophe during dry years. Areas with higher rainfall have a larger margin, and even a relatively large deficiency makes cropping possible. The former case may be exemplified by the meteorological stations in Maseru, Mafeteng and Mhales Hoek, while Leribe, receiving a higher rainfall, is an example of the latter situation. However, the downward trend of annual rainfall is, by far, largest in Leribe, indicating that the station has been receiving (on an average) less and less rain. On a long term scale, a downward trend in rainfall may have an indirect effect on soil erosion through the deterioration of vegetation. The species present in an area, used to much higher rainfall, will experience water stress, start to deteriorate, and eventually be replaced by other species.

The implications of a downward trend in monthly rainfall are similar. A downward trend in December-February makes agricultural production more insecure, since a good crop is highly dependent on sufficient rainfall during these months.

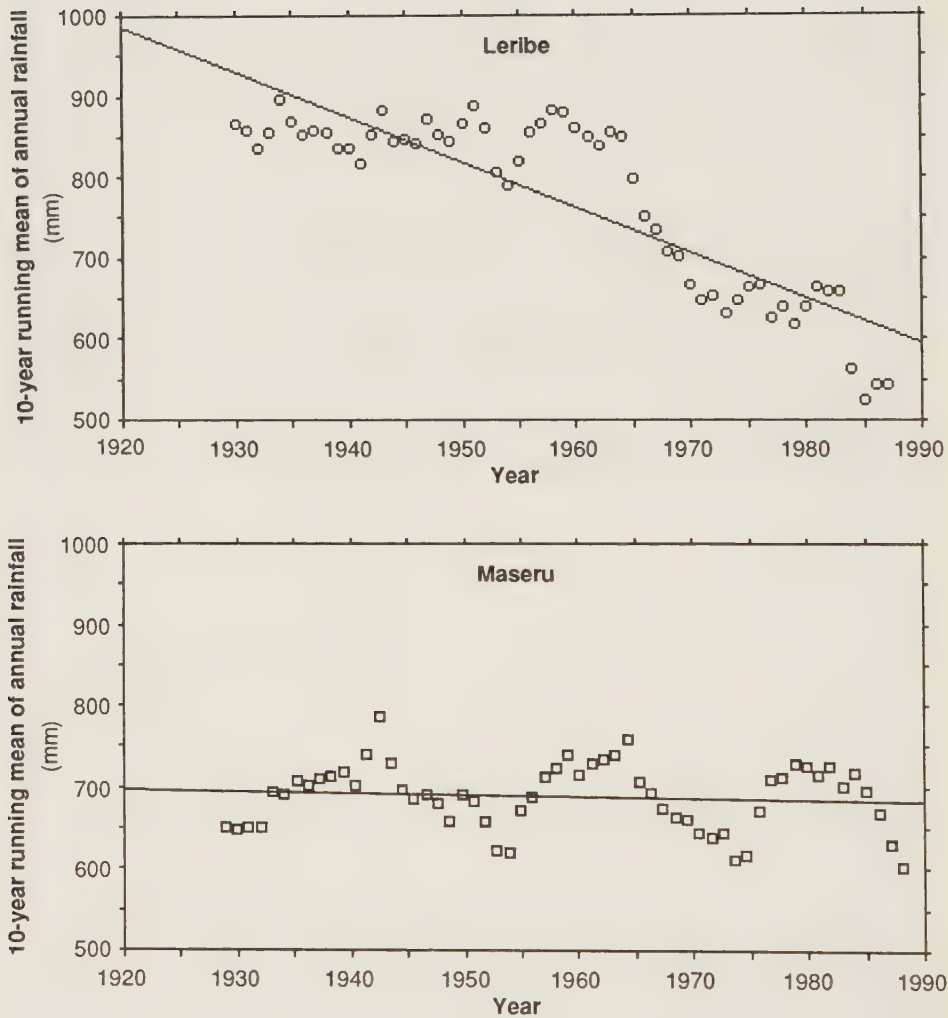


Figure 4.17. Linear trends of 10-year running mean of annual rainfall from 1921 to 1987 at the meteorological stations in Leribe, Maseru, Mafeteng and Mohales Hoek (sources: Hydrol. Survey, 1970, 1988).

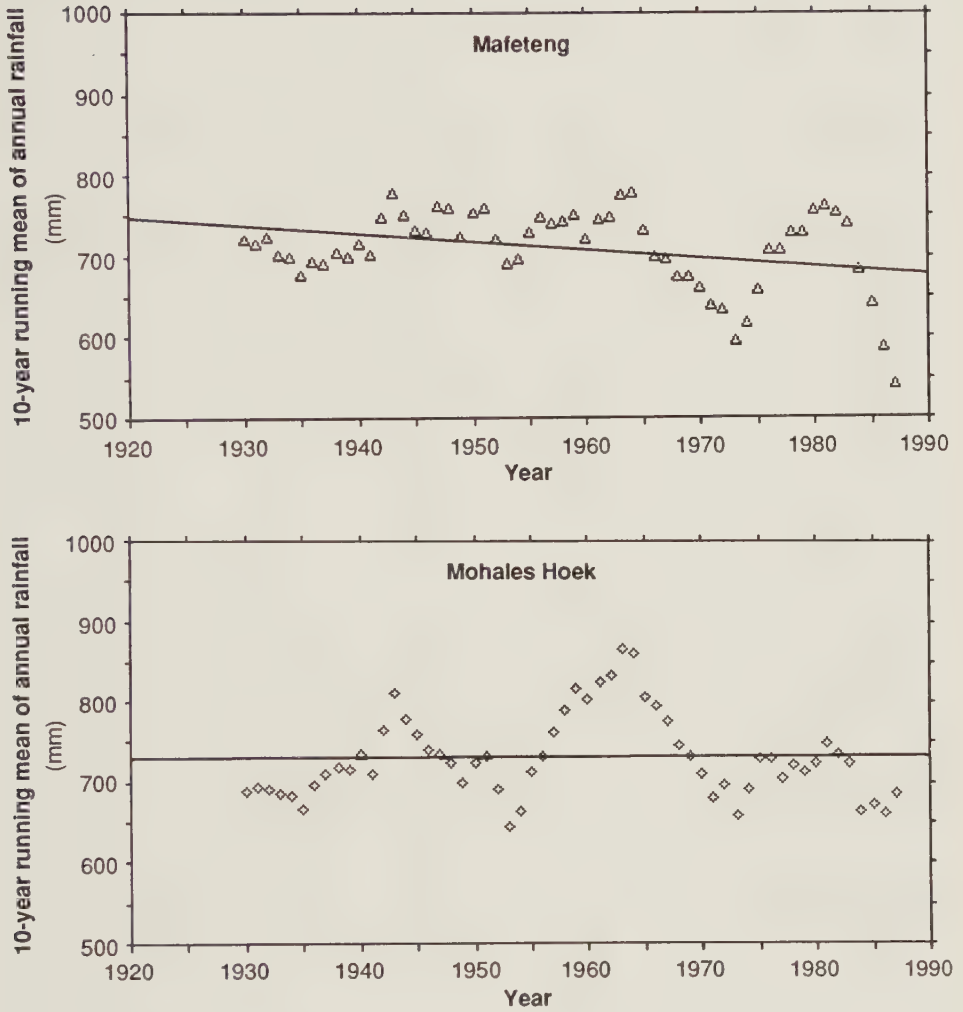


Figure 4.17. Continued.

Table 20. Linear trends, i.e. slope of the regression line and coefficient of explanation (R^2), of the 10-year average annual and monthly rainfall. The slope factor indicates the average trend in mm/year. Calculation based on data from Hydrological Survey Department (1970, 1988).

	Leribe	Maseru	Mafeteng	Mohales Hoek
Annual: Slope	-5.566	-0.196	-0.978	0.056
Coeff. of expl. (%)	74.0	< 1	11.3	< 1
Signif. level (%)	99.9	< 95	99	< 95
January: Slope	-0.053	0.013	0.004	-0.007
Coeff. of expl. (%)	37.0	4.6	< 1	< 1
Signif. level (%)	99.9	< 95	< 95	< 95
February: Slope	-0.038	0.013	-0.027	0.023
Coeff. of expl. (%)	14.4	3.0	7.8	5.3
Signif. level (%)	99	< 95	95	< 95
March: Slope	-0.071	-0.029	-0.040	-0.028
Coeff. of expl. (%)	41.3	15.2	20.8	15.5
Signif. level (%)	99.9	99	99.9	99
April: Slope	-0.007	0.003	0.018	0.023
Coeff. of expl. (%)	1.7	< 1	14.5	34.1
Signif. level (%)	< 95	< 95	99	99.9
May: Slope	-0.012	-0.006	-0.018	-0.022
Coeff. of expl. (%)	7.8	4.6	21.2	22.5
Signif. level (%)	95	< 95	99.9	99.9
June: Slope	-0.008	0.006	0.003	0.013
Coeff. of expl. (%)	14.5	10.4	1.1	31.7
Signif. level (%)	99	95	< 95	95
July: Slope	-0.020	-0.003	-0.005	-0.005
Coeff. of expl. (%)	54.0	6.6	6.9	4.8
Signif. level (%)	99.9	< 95	95	< 95
August: Slope	0.007	0.003	0.013	0.026
Coeff. of expl. (%)	14.6	16.9	< 1	< 1
Signif. level (%)	99.9	99.9	< 95	< 95
September: Slope	-0.003	0.025	0.005	0.014
Coeff. of expl. (%)	< 1	21.3	1.1	10.1
Signif. level (%)	< 95	99.9	< 95	95
October: Slope	-0.027	0.004	0.005	0.017
Coeff. of expl. (%)	13.0	< 1	1.7	17.8
Signif. level (%)	99	< 95	< 95	99.9
November: Slope	-0.091	-0.027	-0.021	-0.024
Coeff. of expl. (%)	64.7	7.8	8.2	9.4
Signif. level (%)	99.9	95	95	95
December: Slope	-0.067	-0.019	-0.025	-0.009
Coeff. of expl. (%)	50.7	9.4	15.7	2.3
Signif. level (%)	99.9	95	99	< 95

5 DISCUSSION

This chapter provides a general characterization of the state of gully erosion in the separate catchments, and a discussion of how the gully development and extent in the catchments correspond with other studies, and apply to larger areas in the lowlands of Lesotho. The impact of different extrinsic and intrinsic variables on gully erosion in the catchments is then discussed.

5.1 Characterization of the state of gully erosion in the catchments

Adapting the theory of cyclic gully erosion and thresholds that have to be crossed for erosion to accelerate, the results of the study would suggest the following characterization of the study catchments in terms of their severity and state of gully erosion, since 1950 up to present time. Figure 5.1 combines the two variables drainage density and gully area and can be seen as a summary of gully development in the catchments since 1950. Figure 5.2 is a schematic illustration of where in the gully erosion cycle the different catchments appear to be at present. The classification of the severity of gully erosion (slight, moderate, severe) in the presentation below is only relative, since all catchments are badly dissected by gullies. Future gully development in the catchments will be through extension and expansion of existing gullies, and initiation of new ones. The discussion on sites in the catchments that may experience a high degree of gulying in the near future, through surface or subsurface erosion, is based on seven indicators: if the gullies have cut down to bedrock; if the gully heads have extended to bedrock; degree of piping; shape of cross-section; availability of material (i.e. erodibility and depth of erodible material); gully development since 1950; and presence of continuous and discontinuous gully heads. The catchments are presented in descending order of severity as regards gully erosion. The local names are presented in brackets.

Maseru 2 (Marabeng)

Maseru 2 was severely eroded in 1950 and continued to erode (mainly through extension) at a very high rate up to 1961. Gully extension slowed down during the second period (1961-1980), while the expansion rate increased slightly. Most of the results of the field inventory and air photo interpretation indicate that the catchment may be in the last phase of a gully erosion cycle. The indices are: a steep average slope above the gully heads, a large percentage of heads that have extended to bedrock, a lower gully head development rate during the second period (1961-1980), an increase in the impact of gully expansion (compared to gully extension) on gully development (extension/expansion ratio), a sharp decline in extension rate, and a decline in the percentage and absolute number of discontinuous gullies. The latter indicates a fusion of discontinuous gully heads. The predominance of the rectangular cross-section in the gullies, caused by the exposure of bedrock in the gully bottom, indicate that gully widening (expansion), rather than extension, will dominate gully development in the future. Potentially very dangerous areas are: the gully system in the south, almost reaching up onto the plateau, which has experienced severe expansion since 1950 due to shallow depths to bedrock; and a zone in the west where few of the gully heads have extended to bedrock and depths of available material are large.

Mohales Hoek 1 (Ha Khitsane)

Mohales Hoek 1 was moderately eroded in 1950. The catchment had very high rates of erosion during the first and second period, and was severely eroded already in 1961. This catchment is second in erosion to Maseru 2, and the two are clearly the most severely eroded of the 8 catchments. Mohales Hoek 1 has a steep average slope above the gully heads, a large percentage of heads that have extended to bedrock, and has shown a decline in the percentage of discontinuous gullies. This would indicate that this catchment is also reaching the end of a gully erosion cycle. However, the gully head development rate was higher during the second period (1961-1980), as was the extension/expansion ratio. The latter was caused by a slightly higher extension rate during the second period. The absolute number of

discontinuous gully heads also increased. Gully erosion, therefore, having been severe since 1950, appears to continue relatively unabated in the catchment. Potentially very dangerous areas are: the badland area in the south-east where numerous gully heads along the main gully have been initiated and piping is extensive; the upper reaches of the three major gullies in the south where few of the heads have extended or cut down to bedrock; and a zone along the northern main gully where several small heads have developed but not yet extended to bedrock.

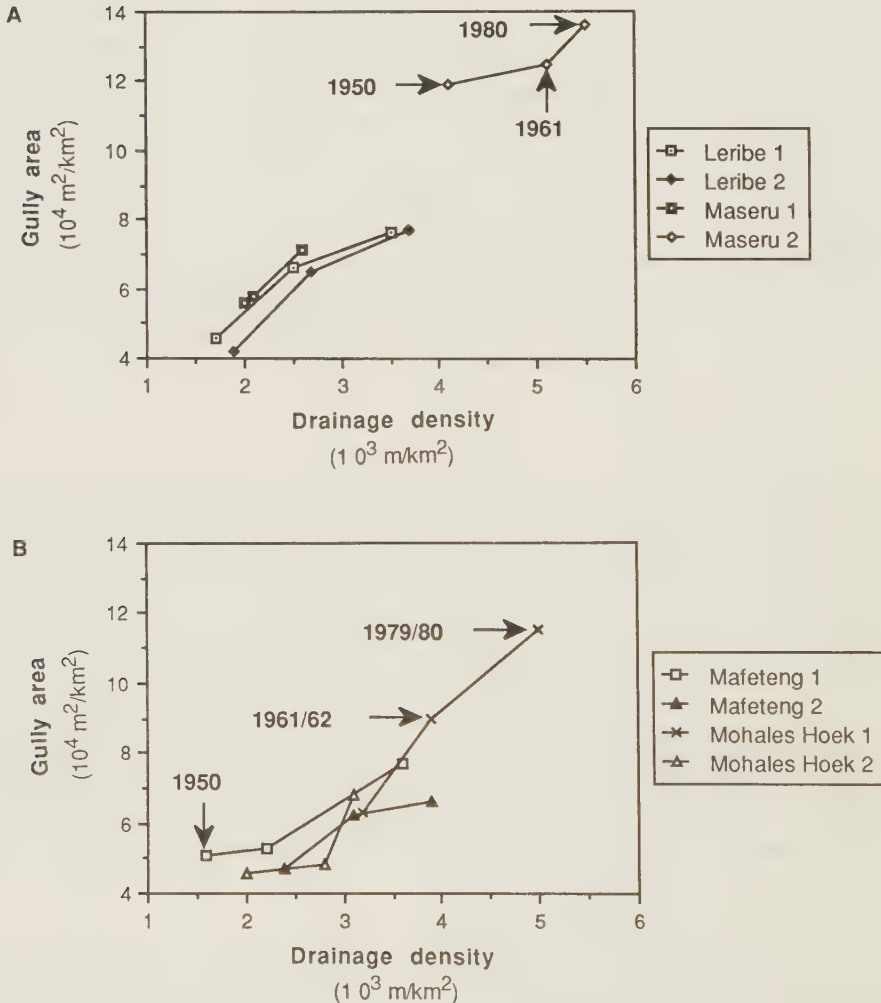


Figure 5.1. Gully development 1950-1980 in A: the catchments Leribe 1 and 2, and Maseru 1 and 2, and B: Mafeteng 1 and 2, and Mohales Hoek 1 and 2.

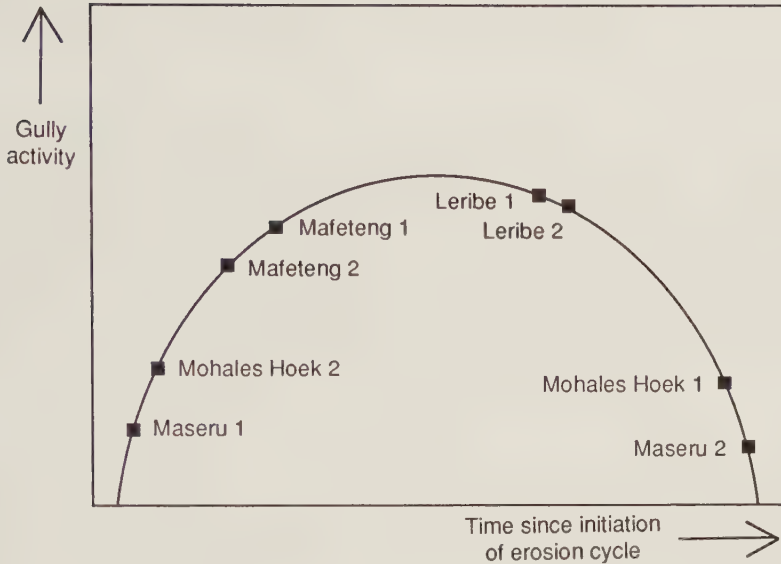


Figure 5.2. Generalized curve of the present position of the study catchments in the gully erosion cycle. The figure is schematic and the catchments have individual cycles. "Gully activity" is a subjective summary (non-numerical) of all the inventoried parameters, i.e. drainage density, gully area, erosion rates, average slope above the headcuts, discontinuous gully heads, if the heads have extended to bedrock etc.

Leribe 1 and 2 (Mathokoane 1 and 2)

The two Leribe catchments are almost identical as far as gully erosion development and severity of erosion are concerned. Both catchments were slightly eroded in 1950. Erosion (extension and expansion) was more intense during the first period (1950-1961) than during the second period (1961-1980), and in 1980 both catchments were moderately eroded. The two catchments also correlate well in almost all inventoried parameters. This applies to average slope above the gully heads, the number of heads that have extended or cut down to bedrock, the increase in extension/expansion ratio, the gully head development rate, and the lower extension and expansion rate during the second period. The increase in extension/expansion ratio is caused by a sharper decrease in expansion rate than extension rate for the second period. The largest discrepancy between the catchments is the percentage of discontinuous gully heads. The percentage has increased in Leribe 1, but decreased in Leribe 2. The absolute number of discontinuous gullies in the catchments, however, has increased since 1950 in both catchments. The fact that the extension/expansion ratio increased in both catchments, and the relatively low percentage of gully heads that have extended to bedrock, suggests that both catchments are in a period of erosion, and have been so at least since 1950. The drainage density and gully area are slightly higher in Leribe 2 and this, in combination with the fact that the absolute number of discontinuous gully heads is larger in this catchment although the percentage of discontinuous heads has been declining, indicates that Leribe 2 has reached further in the gully erosion cycle than Leribe 1. Potentially dangerous areas in Leribe 2 are: the zone of continuous and discontinuous gullies in the north-east, where piping is extensive and where many gully heads have been initiated since 1950, and the area below the escarpment in the

west along the western main gully, where numerous gullies have developed since 1950 but few have extended or cut down to bedrock. The situation is similar in Leribe 1 where severe gullying is likely to occur along the two main gullies below the escarpments in the east and west.

Mafeteng 1 (Matsoseng)

Mafeteng 1 was only slightly eroded in 1950 and had relatively low rates of erosion up to 1961. From 1961 to 1979 severe erosion occurred, both extension and expansion, and the catchment was moderately eroded in 1979. Mafeteng 1 has a low average slope above the gully heads and a low percentage of heads that have extended to or cut down to bedrock. The catchment had a higher gully head development rate, and extension and expansion rates during the second period, and a sharp increase in the number of discontinuous gullies. V-shaped cross-sections are common, indicating that the gullies are fairly young. Gullying is very active in the catchment and it appears to be in the middle of an erosion cycle. Potentially very dangerous areas are: the severely piped area in the east; and the central and northern parts of the catchment which also have a high degree of piping and several newly initiated and small gully heads that have not extended to bedrock.

Mafeteng 2 (Boleka)

Mafeteng 2 was slightly eroded in 1950. The catchment experienced relatively high extension rates during both periods but little expansion during the second period. The catchment was moderately eroded in 1979. Mafeteng 2 has a relatively steep average slope above the gully heads but a low percentage of gully heads that have extended to bedrock. A large percentage of gully heads have cut down to bedrock, reflecting the shallow depths (to bedrock) of erodible material at several locations in the catchment. This is also evident in the relatively high occurrence of rectangular cross-sections, caused by bedrock exposure. Gully head development rate was higher during the second period, but extension and expansion rates decreased. The latter more than the former giving rise to a sharp increase in the extension/expansion ratio. The percentage of discontinuous gully heads decreased, but the absolute number showed an increase from 1961 to 1980. Mafeteng 2 was only slightly eroded in 1950 and moderately eroded in 1961 and 1979, and the extension and expansion rates slowed down during the second period (1961-1979). This would indicate that the catchment is at the end of a gully erosion cycle despite being only moderately eroded. However, the increase in gully head development rate during the second period, the low number of gully heads that have extended to bedrock, and the lower but still comparatively high extension rate during the same period, suggest the opposite, that the catchment appears to be at the beginning of an erosion cycle. Potentially very dangerous areas are: the area around the tributary to the southern main gully that has extensive piping; and the central zone of the northern gully system on top of the bedrock outcrop that has several heads that have not yet extended to bedrock, shallow depths to bedrock indicating future expansion, and piping.

Mohales Hoek 2 (Maphutseng)

Mohales Hoek 2 was slightly eroded in 1950 and showed a very high extension rate but very low expansion up to 1962. The situation was reversed during the second period (low extension, high expansion), and the catchment was moderately eroded in 1979. Mohales Hoek 2 has a low average slope above the gully heads, a low percentage of gully heads that have extended to bedrock, and a high percentage of gully heads that have cut down to bedrock. The gully head development rate was slightly lower, the extension rate much lower, but the expansion rate higher, during the second period. The latter two factors affected the extension/expansion ratio which declined sharply. The absolute number of discontinuous gully heads has increased slightly since 1950, but the percentage has decreased. The prevalence of V-shaped cross-sections may indicate that the gullies are relatively young. This is also shown in the clear dominance of extension over expansion during the first period, creating new gullies instead of widening the old ones. The low percentage of gullies that

have extended to bedrock and the low slope above the gully heads indicate that the catchment is at the beginning of an erosion cycle that will not end until the gullies have extended further upslope and reached bedrock. Potentially very dangerous areas are: the eastern part of the large, central interfluvium where severe gully erosion due to piping has occurred since 1950; the presently relatively limited piped badland zone along the main gully in the south-east; and the bend of the northern main gully where several gully heads have developed but not yet extended to bedrock.

Maseru 1 (Sofonia)

Maseru 1 was slightly eroded in 1950 and the catchment remained in this state through the first period when the extension and expansion rates were low. During the second period the erosion rates were higher and the catchment was moderately eroded in 1980. Maseru 1 has a relatively low average slope above the gully heads, a low percentage of gully heads that have extended to bedrock but a relatively high percentage of gully heads that have cut down to bedrock. Average depth at the gully heads is the highest of all catchments. The gully head development rate was slightly higher during the second period. Extension and expansion rates were also higher. The latter increased more than the former, giving rise to a decline in the extension/expansion ratio. The catchment had relatively few discontinuous gullies in 1950 but the number has increased since then. V-shaped cross-sections are common due to the large depth of the erodible material. Judging by the drainage density and gully area measurements, the catchment was the least eroded of all catchments in 1961 and in 1980, but it appears as if the catchment is now at the beginning of an erosion cycle. The evidence supporting this view is for instance, the increase in discontinuous gullies, and the increase in extension and expansion rate during the second period. Potentially very dangerous areas are: the tributaries and discontinuous gullies in the south-west; the area with several new gully heads in the west that have not yet extended to bedrock; the two discontinuous gullies in the north; and the gully head on the eastern side of the main gully that recently (1988) experienced severe extension.

How do these results apply to other parts of the lowlands of Lesotho? Chakela (1981) studied gully extension in four catchments in the Koeneng and Khomo-Khoana river basins in the northern lowlands of Lesotho, and in six catchments in the Roma Valley. The four northern catchments are situated just south (2-12 km) of the two Leribe catchments examined in this study, and the catchments in the Roma Valley about 20-30 km south-east of the two Maseru catchments. The extension measurements were based on air photo interpretation and field studies. In the four catchments in the north Chakela found that gully extension had been low between 1951 and 1977, 62 % of the gullies had extended less than 5 m and only 5 % more than 50 m. No newly gullied areas were found and discontinuous gullies were few. The reasons for the low rate of gully extension were that most of the gullies had extended to bedrock and reached closer to the divide, and that all areas liable to gully erosion had been gullied (*ibid.*). In the catchments in the Roma Valley 76 % (16/21) of the gullies had extended more than 30 m during the period 1951-71, and only one gully (5%) had extended less than 10 m.

The two studies by Chakela thus showed that gully erosion rates were entirely different in the two areas. In the northern area rates were low and the gully systems appear to have been at the end of an erosion cycle, having to a large extent extended to bedrock. The two Leribe catchments used in this study, situated north of the catchments used by Chakela and draining into a different valley, are on the other hand in a very active period of gully erosion, and in the middle of an erosion cycle. In the Roma Valley the gullies were very active in the early 70s and apparently in the middle of an erosion cycle. This can be compared with the two Maseru catchments used in this study, which are at the beginning and end of an erosion cycle respectively.

Another example is a gully system in a suburban area of Maseru studied by Ntsiki and Mokone (1986). They found that gully growth rates were higher during the period 1950 to 1974 than from 1974 to the present day and suggested that the decrease was due to the gullies having extended to bedrock and attained equilibrium between width and depth. The area would thus appear to be at the end of an erosion cycle.

Lundén et al. (1986) found that gully expansion was three times as fast during the period 1950 to 1961 in the catchment Mohales Hoek 1 (Ha Khitsane), compared with the period

1961-1980. The results presented in this study show that expansion rate was twice as high but the extension rate slightly lower during the first period compared to the second. Sarr (1986) made a survey of gully erosion in an area covering 36 km² in the southern lowlands of Lesotho in which the catchment Mohales Hoek 1 is included. For the whole area gully development during the two periods was constant. Lundén et al. (1986) concluded that the difference between gully development in the larger area and the smaller catchment (Mohales Hoek 1) clearly indicated that the threshold for gully erosion to increase is reached at different times in different areas, i.e. there is a variation in gully erosion in both time and space between different areas even within the same region.

Another gully erosion survey was carried out in the Thaba Bosiu Rural Development Project Area (just east of the Maseru 1 catchment). Makhanya (1979) found that the extent of severe gully erosion in some sample areas varied from 2 to 26 %. This can be compared with the inventory of gully area, using grid squares and the SARCCUS classification system, carried out in this study. The extent of the severe gully erosion class ranges from 4 to 20 % between the eight catchments (Table 14). The class limits for "severe gully erosion" may not be identical in the two studies but the results illustrate, once again, how gully erosion may vary between different areas.

Schmitz (1980) claims that most of the gullies in Lesotho are actively eroding but that the main phase of expansion is over. This does not appear to be true. Gully erosion in the Lesotho lowlands is very variable in time and space. The separate catchments are individual systems with individual thresholds and intrinsic and extrinsic conditions for gully erosion. The results of local gully erosion studies cannot be assumed to apply to larger areas (regional, national) other than at a general level, i.e. the environment is vulnerable to gully erosion and the process is active in some areas and stagnant in others.

5.2 Factors affecting gully erosion in the catchments

The factors affecting gully erosion in general were discussed in Chapter 2.4. The discussion below is based on the results presented in Chapter 4, and apply to the 8 catchments examined in this study. Two basic prerequisites are necessary for gully erosion to be possible. There has to be material available in which the gullies can develop, and there has to be an eroding agent, i.e. surface or subsurface runoff. The factors discussed below affect these two prerequisites, more or less, and in different ways.

5.2.1 Morphology of the drainage basin

From the results of the analyses of gully erosion in the catchments it is clear that gully erosion does not require steep slopes. Gullies and gully heads were found on very low slopes (< 2 %). A steep slope above a gully head naturally increases the erosivity of the runoff entering the gully, and thereby may affect the head cutting rate. However, as the gully extends further upslope, the area drained and the slope length are reduced. This, in turn, reduces the head cutting rate as less water will be collected at the head cut. Therefore, a steep average slope above the gully heads in a catchment should be seen as a sign that the gully heads have extended and reached closer to the drainage divide, rather than as a factor that has contributed to the acceleration of gully erosion in the catchment. At an earlier stage in the gully erosion cycle the average slope above the gully heads in the catchments would have been lower since the gullies had not extended as far upslope as at present.

In general the higher the drainage density the more severely eroded a catchment is, the further the gullies have extended, the closer the gully heads are to the drainage divide, and, consequently, the steeper the average slope above the gully heads. The statement is, however, to some extent, an oversimplification since a high drainage density may be caused by a few but long gullies, extending far upslope, or by numerous short gullies. Nevertheless, it is valid for the two most severely eroded catchments Maseru 2 and Mohales Hoek 1. These catchments, in addition to being the most severely eroded and having the highest drainage densities and largest gully areas, also have, by far, the highest percentages of gully heads that have extended to bedrock, i.e. reached their ultimate extension. Leribe 2, on the other hand, may serve as an example of a catchment with a relatively high drainage density but a low average slope above the gully heads. This is despite the fact that the catchment has the

steepest average slope (for the whole catchment) of all the eight catchments on study. The high drainage density reflects the very dense network of short continuous or discontinuous gullies found on the slopes along the main gullies, tributaries that do not extend far upslope. It is dangerous, therefore, to draw conclusions as to the severity of erosion, and where in the gully erosion cycle a catchment is at present, by simply weighing the drainage density or gully area. Other factors have to be taken into consideration, for example, the average slope above the gully heads and the extension to bedrock.

If slope does not have a pronounced direct impact on gullying in a catchment it may still contribute indirectly. The erodible material is concentrated, by fluvial transport or slope processes, in the flatter parts of the catchments, and a lot of material is made available for gullying. This is also where clayey soils are found and duplex soils have time to develop. The soils and the fact that more water is available and has time to infiltrate in the flatter and central parts of the catchments, make the conditions favourable for piping. This is also reflected in the negative correlation between piping and slope found in the four catchments where grid square analyses were carried out. In short, the effects of slope on gullying are not immediate. Indirectly a marked macrotopography of the catchment will give rise to a concentration of available material in the flatter parts of the catchments, as well increased infiltration. Both factors increase the potential for gullying in the central areas of the catchment.

Slope length is probably an important factor that affects gullying. Mainly by causing a build-up of runoff, it increases the erosivity. The effect of slope length in the study catchments is difficult to assess, however. All cultivated slopes in the catchments have grass strips or terraces, and the conclusions can only be speculative. The main gullies have developed in the lower parts of the catchments, probably before the grass strips/terraces were installed. At that time slope length may well have been a major contributing factor to gully erosion. Furthermore, the grass strips do not, from the onset, serve the purpose of diverting the runoff from the fields, but of trapping the sediment. As more and more sediment is trapped, the grass strips develop into terraces. At the beginning, therefore, slope length is not reduced but the runoff slowed down at the grass strips. In the lower and flatter parts of the catchments there may be a high build-up of runoff, however, and consequently a high potential for gully erosion, despite the grass strips. Once the main gullies have developed, new gully heads and gullies are easily initiated through piping or surface runoff along the main gullies. The two Leribe catchments may serve as examples of the impact of slope length on gully erosion. Both catchments have a large interfluvium in the centre, and two main gullies running on each side of this interfluvium. Numerous tributary gullies have developed on the slopes facing the interfluvium, below the escarpment, while few tributaries have developed and extended on the slopes of the interfluvium. The difference was apparent already prior to the installation of grass strips in the 50s, but it has been accentuated since then, despite the grass strips.

The bedrock topography and slope in a catchment both influence the depth of alluvial and colluvial deposits in the basins. This in turn may affect the gully eroding processes in the catchment. Where the deposits are deep (and erodible), gully lengthening and downward scouring are more prominent than gully widening. This is reflected in the grid square correlation analyses between gully depth and gully length, and between gully depth and gully erosion according to the SARCCUS classification (i.e. gully area). The correlation is higher between depth and length than between depth and area (Table 17) in all four catchments analysed.

The local bedrock topography also affects gullying in a catchment more directly since gullies may be discontinuous due to bedrock outcrops (Fig. 2.1). In continuous gullies, where bedrock outcrops do not reach the soil surface but are locally exposed in the gully bottom, the runoff along the gully bottom is no longer capable of downward scouring due to the resistant bedrock and the eroding forces are transferred to the gully walls. The gully may be widened locally as the runoff in the bottom undermines the walls. This is the case in Mafeteng 2 for example where bedrock at a shallow depth has also acted as an impermeable layer and caused piping.

5.2.2 Climate

Precipitation is the most important climatic factor that affects erosion, but it is difficult to assess the direct effects of different rainfall properties on gully erosion in the catchments. As mentioned in Section 3.1.2 no intensity measurements are available for Lesotho. Smithen

and Schulze (1982) produced a map showing the EI-30 isolines for South Africa in which Lesotho is included (Fig. 3.3). The map has a very small scale but it is clear that the average annual EI-30 value (i.e. rainfall erosivity) in the lowlands decreases towards the north, according to the map. The meteorological stations and catchments in Mafeteng and Mochales Hoek have an annual estimated EI-30 average of just over 200, while the catchments in Leribe and Maseru have an EI-30 just over and just under 150 respectively. In other words, the two catchments in Mochales Hoek and the two catchments in Mafeteng are subject to rainfall of a slightly higher erosivity than the catchments in Leribe, which in turn receive more erosive rain than the catchments in Maseru. If all other extrinsic and intrinsic variables in the catchments were equal this would imply, theoretically, that erosion would be greatest in the catchments in Mochales Hoek and Mafeteng, and lowest in Maseru.

One severe problem in Lesotho regarding erosion is the high variability of the rainfall. As mentioned earlier (Sect. 4.5.3), areas that receive little rain are more sensitive to drought conditions than areas with higher rainfall. The former are balancing closer to the edge of crop failure and vegetative deterioration during spells of below normal rainfall. As a consequence of the low rainfall and reduced vegetation cover, the carrying capacity of the ranges declines and the grazing pressure is intensified. The meteorological stations and catchments in Maseru, Mafeteng and Mochales Hoek, having a lower annual rainfall, would therefore appear to be more vulnerable to negative deviations in rainfall than the station and catchments in Leribe. The variability of annual rainfall, however, is higher in Leribe than at the other three stations, but this is not as crucial since the annual rainfall is relatively high.

The effects on gully erosion of the dry/wet spell interval of 18.65 years suggested by Tyson and Dyer (1975) are probably not as significant as the actual variations from year to year, or month to month, within the spells. A wet year within a dry spell will cause more damage than another dry year, and a dry year within a wet spell will create favourable conditions for erosion during the subsequent wet year. Eckert (1982) claims that there are fewer deviant years within the wet or dry spells now than at the beginning of the century, i.e. the spells are becoming more consistently wet or dry. He also suggests that the amplitude of the oscillation may be increasing. The implication of the former statement is that the deviant years (from the wet/dry spell) are becoming scarcer, a situation that may have a negative effect on soil erosion (i.e. less erosion) since it is the deviant years that are critical. An increasing amplitude of dry spells in particular, would, however, have a positive effect (increased erosion potential) as the water stress will be greater for the vegetation.

The results of the rainfall analyses of dry-wet (monthly) sequels are inconsistent. All meteorological stations except Mafeteng had a higher number of monthly dry-wet sequels during the second period (1961-80) than during the first (1950-61). Mafeteng had the highest total of potentially erosive events (21) between 1950 and 1980, followed by Maseru (20). Due to a lack of rainfall data for Leribe between 1975 and 1981, no dry-wet sequels were detected at the station between 1975 and 1980. Two such sequels appear during the same period in the records from the other three stations and it is probable that the same events also occurred in Leribe. Assuming that they did occur, Leribe and Mochales Hoek had the lowest total number of potentially erosive events between 1950 and 1980 (15/14). The catchments for this study were selected in pairs with presumably similar climatic conditions, but only the two Leribe catchments show the same gully development during the two periods (1950-61, 1961-80). The catchments in Maseru, Mafeteng and Mochales Hoek show a different pattern between the catchments within each pair. The two catchments in Leribe are situated very close to each other and the rainfall should be very similar in the catchments. The same is valid for the catchments in Maseru but, despite this, gully development has been entirely different in the two. Maseru 1 is the least eroded, while Maseru 2 is the most eroded of all eight catchments. The catchments in Mafeteng are situated further apart, and the catchments in Mochales Hoek even further, on opposite sides of the meteorological station. The rainfall may vary slightly between the catchments within each pair due to local storms, but the dry and wet periods and monthly and annual deviations from mean, are probably the same. Mafeteng 1 is third in erosion, Mafeteng 2 sixth, Mochales Hoek 1 is second in erosion and Mochales Hoek 2 seventh. The difference in erosion between the two catchments in Maseru, Mafeteng and Mochales Hoek cannot possibly be ascribed solely to local variation in rainfall. The differences in erosion must be due to a combination of other factors.

The stations in Leribe and Mochales Hoek have the highest average annual rainfall. It also appears as if these stations have less monthly deviations within wet or dry years, i.e. the years are more consistently dry or wet, than in Maseru and Mafeteng. Mafeteng, on the other hand, had one or two potentially erosive events almost every year between 1950 and 1961, despite

the low annual rainfall in 1951 through 1954, and 1959-60, and the wet period from 1955 through 1958. This illustrates the insufficiency in analysing only the annual rainfall deviations from normal. A more detailed analysis is necessary, at least on a monthly basis. It is most probable that separate rainfall events also may cause severe erosion but since rainfall data is not available on, for example, a daily basis, for the stations used, a more detailed analysis of rainfall was not possible. Whether there is a definite relationship between higher annual rainfall and smaller monthly deviations within the wet or dry year, is impossible to say since only four stations were analysed. This is far too few and the time period (30 years) is too short to render the result statistical significance. A more thorough investigation is beyond the scope of this study.

There is evidence that the climate in Lesotho previously was more humid and warmer than the present day climate. One example is the presence of an argillic horizon in certain lowland soils (Schmitz & Rooyani, 1987), another the pattern of vegetation migrations (Acocks, 1975). The annual rainfall trends since 1921 are negative at the meteorological stations in Leribe and Mafeteng, the former very steeply so. The result indicates that the climate in the northern lowlands is getting drier at a rapid rate. However, only one station was analysed and the time span is too short to draw any such radical and definite conclusions. Nevertheless, if this is the case there will probably be a change in vegetation type and cover, and this will presumably make the soils more vulnerable to erosion. It is not reasonable to speculate whether the drier climate will increase gully erosion in the future since it cannot be stated with certainty if intensity and erosivity will increase as rainfall decreases. Brook and Mametse (1970) made calculations of rainfall trends for 93 stations in South Africa, using 10-year averages. They found that 49 % of the stations had experienced an average negative trend of 1.85 mm/year during this century. The zone of negative rainfall trend covers roughly the north-eastern part of South Africa and a belt from east to west just south of Lesotho. It barely reaches across the north-eastern border of Lesotho. This is not in concordance with the results of this study since the northern and central lowland stations in Leribe and Mafeteng have apparently also experienced a decrease in rainfall. Brook and Mametse (op cit.) claim that the pattern of positive and negative trends that they found is the result of the large scale atmospheric circulation.

5.2.3 Geology and soils

That soil type has a great influence on gully erosion is evident when considering the distribution of gullies in Lesotho as a whole, i.e. the extent of gullying in the mountains compared to the lowlands. The distribution is to a large extent due to the difference in soils and general availability of material (Schmitz & Rooyani, 1987). All eight study catchments are situated in the lowlands and the two soil parameters used were erodibility and if the soil had a duplex nature. The analyses were carried out using grid squares in the four catchments for which soil maps are available, Leribe 1, Maseru 1, Mafeteng 1, and Mochales Hoek 1. The correlation between gully erosion and duplex soils is slightly higher than the correlation with soil erodibility, but none of the correlations is particularly high. It would therefore appear that duplex soils and other erodible soils are not a prerequisite for gullying, but this is a simplification. The gullies may have developed in duplex or erodible soils and then extended and expanded into non-duplex or less erodible soils, giving rise to a lower correlation coefficient. The imperfect correlation between gully erosion and duplex soils is also the result of grid squares that have duplex soils but no gully erosion. Furthermore, the main gullies have developed in the central parts of the catchments. This is also where a large portion of the duplex soils are found and the correlation should therefore be rather high. However, gullying in the central parts of a drainage basin is not necessarily a consequence merely of the presence of duplex soils, since other factors such as the macrotopography may have influenced the original development of the main gullies and the distribution of duplex soils.

The inventory of piping is only a minimum measure, since only clearly detectable signs (i.e. an inlet or outlet) along the gully stretches were recorded as piping. Piping is probably more extensive in the catchments than the indices show. There is a very low correlation between piping and duplex soils, indicating that piping is not confined to duplex soils alone. This is especially the case with the deep kind of piping, which is not dependent on duplex properties of the top soil, since the pipes develop deeper down in the parent material due to the favourable conditions there. The extensive piping in the two Leribe catchments, for example, has developed in shale on a silt/mudstone layer underlying sandstone alluvium.

Cracks and fissures in the shale have developed into pipes, receiving water from the overlying and permeable sandstone alluvium. The development of giant pipes in this layer is probably at the expense of smaller ones, since larger cracks and fissures collect more water. This process is accentuated as the pipe grows. For deep piping to develop, however, there has to be an exposed gully wall, i.e. an already developed gully has to be present. Shallow piping on the other hand may develop anywhere on a slope, where the soils and hydraulic conditions are favourable.

Limited depths of available material (i.e. the depth of soil and erodible parent material down to resistant bedrock) give rise to gully widening instead of downward scouring. This is reflected in the higher correlation between gully length and gully depth than between gully area (SARCCUS classification) and gully depth. In other words, large depths in the grid squares are more often found in connection with long and narrow stretches of gullies than with wide ones. A shallow depth to resistant bedrock restricts downcutting. The bedrock surface is smooth and the velocity and erosivity of the flow are high. The debris along the gully walls has been effectively removed and the gully walls are easily eroded and undermined. This is the case in Maseru 2 where the high percentage of rectangular cross-sections at the gully heads is caused by exposed bedrock in the gully bottom.

The effects of bedrock topography and slope on gully erosion and piping have already been discussed in a previous paragraph. The type of bedrock may affect gullying indirectly through its influence on the soil type. For example, all the duplex soils found in the catchments have originated from shales, mudstone, grits, and sandstone from the Burgersdorp, Molteno, and Elliot formations, while the less erodible Matela soil found in Maseru 1 is sandstone derived (Clarens formation). The different bedrock types give rise to different clay types and clay contents in the soils and may therefore indirectly affect piping and, as a consequence, gullying.

5.2.4 Baselevel

Five of the catchments in the study have reservoirs built in the 50s that are now filled with sediments. The catchments are Leribe 1, Maseru 1 and 2, Mafeteng 1, and Mohales Hoek 1. Theoretically, if the influence of a baselevel change could be felt a long distance upstream, the baselevel would be the ultimate determinant as to whether and to which extent gully erosion in the drainage basin would increase or decrease in conjunction with a raised or lowered baselevel. As a consequence of the reservoirs in the study catchments, the erosion rates would have been lower during the second period (1961-1980). The results are inconsistent. Erosion rates, extension and expansion, decreased or remained constant in Leribe 1 and Maseru 2, but increased in Maseru 1 and Mafeteng 1. In Mohales Hoek 1 the extension rate increased while the expansion rate decreased. In the catchments, sediment has been deposited in the dam and in the immediate vicinity of it. The sediment in the dam and in some of the tributary gully mouths has a relatively dense grass cover and appears to have been stabilized by now. The effects are of a local character, however, but may be followed further upstream in the main gully than in the tributaries. This is probably the result of the lower slope of the main gully bottom compared to the tributaries. No definite conclusions can be drawn as to how far upstream the effects can be observed, since no detailed studies were carried out on the matter. However, the results appear to support the conclusions drawn by Leopold and Bull (1979) that a baselevel rise can only be felt a limited distance upstream, i.e. it is of a very local character.

Certain locations in the study catchments have neighbouring, small tributary gullies of entirely different depths. In Mafeteng 2 for example, three parallel and narrow gullies within a distance of 4-5 m of each other have depths of approximately 3, 1.5 and 0.5 m. The deepest gully has cut down to bedrock. This is an example of a local baselevel and it is reasonable to assume that the two other gullies will continue to cut down to the bedrock surface. Another example indicating a very local baselevel lowering is some of the gullies in the severely piped area in the eastern part of Mafeteng 1. Several, apparently almost stable, gullies with grass vegetation in the bottom are experiencing new headcutting along the gully bottom. The reason for the baselevel lowering is impossible to determine with certainty, but since piping (both deep and shallow) is extensive in the area, one possible explanation is the collapse, at some point, of pipe roofs along some of the major gullies in the area. This caused a sudden baselevel lowering as the pipes turned into open gullies. The stable gullies may well have existed before the collapse of the pipe system started, and the gullies are now being

reinitiated. Cases similar to the examples given, where local baselevel differences have caused or may cause accelerated erosion can be found in all study catchments.

5.2.5 Vegetation

It was not possible to determine the amount of vegetation in 1950, 1961/62, and 1979/80 in a useful way using the air photographs, due to the shifting quality of the photos, neither would it have proved particularly interesting, since the years in between would still have remained unknown. Since most of the gullies have developed in the cultivated fields, one possible approach would have been to use maize yields (in kg/ha) as a measure of the vegetation cover. However, such figures are only available on a 10-year basis prior to 1974 and furthermore only for Lesotho as a whole, not by district. Unfortunately, therefore, no figures on ground cover during the two periods (1950-1961/62, 1961/62-1979/80) are available for the study catchments. Vegetation and yields to a great extent depend on rainfall and the factor of rainfall will have to suffice. The direct effect of overall vegetative ground cover on gully erosion in the catchments remains to be investigated. Some obvious, local effects of vegetation on gully erosion are presented below.

Some of the major tributary gullies in Leribe 1 and 2, and Maseru 1 have bush vegetation and small trees on the bottom and on the sloping gully walls. Along these stretches, the gullies appear to be relatively stable. In the upper reaches of these gullies, however, where the small tributaries have not yet extended to the escarpment, erosion is still active. Nevertheless, the trees and bushes on the gully bottom, where found, appear to locally halt the erosion.

Around and along the sides of several of the gullies in the same three catchments poplars have been planted in order to prevent further gully widening and erosion. Unfortunately these efforts have not been very successful. Several small patches of poplars are found in pipe inlets and sink holes, apparently having fallen vertically as the pipe roof collapsed. This is very common and often the only visible sign of piping along the gullies. Since the deep kind of piping is prominent in these three catchments, the deep, penetrating roots of the planted poplars seem to promote, rather than prevent, the development of pipes and, consequently, gullies. The roots break through the top horizon of the soil and the clayey B-horizon of the duplex soils and facilitate the percolation of water to piping-prone horizons deeper down in the profile. The roots are also thick and the decaying root holes may thereby act directly as pipes.

If the deep kind of piping is promoted by tree growth that enhances infiltration, the shallow type appears to be so by the absence of vegetation and presence of sheet erosion. The two conditions lead to increased desiccation cracking, if the soil conditions are favourable, and hence small pipes are likely to develop. Severe sheet erosion is often found in association with extensive piping in the badland areas in Mafeteng 1 and Mophale Hoek 1.

Tree plantations are found in two of the catchments, Leribe 1 and Maseru 1. In the former catchment, planting in the two woodlots was started in 1976 and 1979 and completed in 1981 and 1984 respectively. In Maseru 1 planting was initiated in 1977 and completed in 1981. In both catchments the period that the woodlots have existed, up to 1980 when the last panchromatic air photos were taken, is too short to draw any conclusions about whether gully erosion in the two catchments has been affected, positively or negatively. Field checks in the catchments, however, revealed that gullies extending into the woodlots are still active, and that piping was found at some of the gully heads in Leribe. It is probably too soon yet to tell whether the planting of trees will prevent gullying more efficiently than for example a dense grass cover. However, judging by the observations in the field, the soils in the lowlands of Lesotho are extremely vulnerable to piping and trees appear to accelerate this process, especially the deep kind of piping. A dense and healthy grass cover would seemingly function better as a conservation measure. The roots are thinner and do not penetrate as deep, and the water is used efficiently, which helps avoid excess percolation to piping-prone soil horizons.

5.2.6 Human Impact

An increase in population may not have immediate effects on gully erosion, detectable within the timespan of this study (1950-1980). However, the population increase in Lesotho

has led to severe land shortage, the cultivation of marginal lands, an increase in livestock, and thus, indirectly, a general degradation of the cultivated fields and pastures, deterioration of soils, and accelerated erosion. The population in Lesotho has shown an exponential increase from about 35 000 in 1835 (Germond, 1967) to just under 1 500 000 in 1986 (Bur. of Stat., 1988)(Fig. 3.5 A). The population density, in the districts where the catchments are located, is lowest in Mochale District and has been so since the 60s. The Mafeteng District has had the highest population density since 1935. The increasing population has led to a continuous decrease in the cultivated area per farm household in Lesotho, from 2.4 ha in 1950 (Morogole, 1963a) to about 1 ha in 1986 (Bur. of Stat., 1987b)(Fig. 3.6). The average number of fields per farm household has not decreased at the same rate. As a consequence, there has been continuous land fragmentation as the same number of fields was allocated but of smaller sizes. This may well have had devastating effects on gully erosion, where the continuity of the cultivated areas has been disrupted by field borders running across and down the slopes. This can be observed in Mafeteng 1, for example, where several of the gullies have clearly developed in straight lines along field borders running down the slope.

An increase in population also leads to an increase in livestock. In the mid-1800s, the stock number was low and the stock were able to migrate, and so the pastures could recover in between. There was a dramatic increase in animal units in Lesotho up to the crash in the mid-1930s (Fig. 3.5 A). Since then there has been an irregular increase but the total number of animal units has not yet reached the peak of the 30s. Tiedeman (1983) speculates that the livestock population in Lesotho, due to the severe overgrazing of the pastures prior to the drought in the 30s, has reached a new, lower equilibrium. A comparison between annual rainfall and animal units, reveals that the peak in number of animal units in the end of the 40s actually occurred during and after a series of dry years in Maseru and Mochale Hoek. The same is true at all four meteorological stations used in this study, for the peak in animal units in 1970. The low in 1940, on the other hand, happened after a period of years with rainfall above normal in Leribe and Mochale Hoek. The low in 1960 and 1977-78 coincided with a period of relatively wet years. Thus, there appears to be a time lag between rainfall and livestock increase or decrease. Unfortunately, livestock imports and exports in Lesotho complicate the matter and livestock increases/decreases are not entirely due to natural causes. Nevertheless, a livestock peak during a dry period when the vegetation cover is already reduced, will obviously have severe effects on erosion.

It is clear from the results of the study that gully heads are often found in connection with terraces (Table 11). The low percentage in the catchments Maseru 2 and Mochale Hoek 1 is probably due to the fact that the gullies in these severely eroded catchments have mostly extended past the cultivated fields and terraces. It is often impossible to determine in the field if the terrace was the original cause of the headcut, but the terrace may, nevertheless, have assisted in the erosion process by collecting and concentrating the runoff. The percentage of gully heads found at terraces during the field inventory includes both types of gully heads, gullies clearly initiated at the terrace, and gully heads found in connection with the terrace, but not necessarily initiated there. In piping-prone soils a terrace that causes infiltration instead of diverting the flow properly is likely to initiate a headcut. This may be seen at several locations, for example, in Mafeteng 1 and Mochale Hoek 1. In the former case, it has given rise to extensive pipe development and local badland areas. On the other hand, a terrace that is underdimensioned for the flow it is supposed to divert may cause gully head development through surface runoff. The water spills over the terrace edge and a headcut is initiated just below. This can be seen, for example, in Maseru 1, where some small discontinuous gullies have developed through this process. As a result of the increased flow through the headcut and into the field below, the next terrace downslope is also underdimensioned for the amount of water it receives and may experience headcutting. The terraces may also divert the water flow properly, but the flow causes linear erosion along the terrace and a gully develops. This can be seen, for example, in Mochale Hoek 1 and Maseru 1 (Fig. 5.3, 5.4). The terraces are frequently used for grazing and foot paths, which tends to reduce the protective vegetation cover and further accentuate the problem. It is clear from the discussion above that the construction of terraces as a conservation measure is not undisputed in the context of gully erosion in the Lesotho lowlands.



Figure 5.3 Terrace functioning properly in Maseru 1 (Jan. 30, 1985)



Figure 5.4 Terrace that has induced gully erosion in Maseru 1 (Jan. 30, 1985)

In Mohales Hoek 1, grass strips and terraces were installed before 1950. Despite this the catchment has been the second most eroded catchment since 1950, and erosion has not ceased. This would imply that the grass strips have had little effect as a conservation measure, at least as far as gully erosion is concerned. Three possible explanations that apply to all catchments can be found. Firstly, the field borders were not adapted to the grass strips, i.e. they were not delineated along the contours, and runoff and erosion along the field borders was able to continue. Secondly, the very piping-prone soils reacted to the increased infiltration, and gully head development through piping was intensified. Finally, the grass strips were not sufficiently effective in reducing and slowing down the runoff. The runoff may have disposed of some of its sediment load at the grass strip and, hence, had a high erosion potential as it entered the field below, thereby initiating a gully.

Roads, paths and cattle tracks frequently lead to the initiation of discontinuous gullies by collecting and concentrating the runoff. New headcuts often start at foot paths entering existing gullies and collecting the runoff. As the tributary gullies provide ideal sites for foot paths to gain access to the other side, the problem is accentuated.

Cultivation is relatively easy to distinguish as the direct initiator of a gully or headcut. Frequently, for example in Mafeteng 1 and 2, plough furrows in a depression in a field deviate from the slope contour. Neither the depression nor the deviation of the furrows has to be large. The runoff is immediately collected, and a rill is initiated that will develop into a gully if it is not eliminated at the next ploughing. By that time, however, the rill may already have grown too large. One further effect of ploughing is that the plough pan may accentuate the influence of a clayey B-horizon in a duplex soil. In some of the badland areas in Mohales Hoek 1, where the A-horizon has been removed, this can be seen as a striation along the contours at the top of the exposed B-horizon, apparently emanating from ploughing.

Germond (1967, p. 72) speculates that the introduction of the plough in the mid-1800s contributed significantly to erosion in general in Lesotho:

"Until the event of the plough,..., the slopes remained comparatively intact and there was ample reason for this: - the small extent of the arable land in general; - the diminutive size of individual patches; - their irregularity; - the use of the native hoe; - poor technique; - the practice of maintaining a strip of virgin veld to mark the boundaries and to protect the crops against stray animals; - the custom of shifting cultivation, thanks to which the fertility and structure of the soil were maintained and restored. These factors undoubtedly combined to minimize the consequences of a malpractice which, before the end of the century, was destined to rob Basutoland (Lesotho) of much of its precious soil."

The introduction of the plough made cultivation more efficient and the fields could expand, exposing the vulnerable soils. The plough furrows created potential rill and gully sites. As early as the mid-1800s, however, prior to the introduction of any "modern" conservatory farming practices, the farmers in Lesotho tended to plough across rather than up the slope (Chakela and Cantor, 1987). Beinart (1984) further suggests that the introduction of the ox-drawn sledge in the mid-1800s for transportation to and from the fields, contributed to the formation of gullies. The sledge was easier to pull up and down the slopes, rather than at an angle across, thus wearing down the vegetation and the soil and creating incipient gullies. Ploughing may also have increased gully erosion through subsurface flow. Nir and Klein (1974) noted that contour ploughing in Israel, by favouring infiltration, greatly increased gully erosion through piping. It can be speculated that this also may have been the case on the piping-prone soils in Lesotho.

Livestock numbers in the mid-1800s were relatively low, but gully erosion was already obvious (see Section 3.1.6). Since most of the gullies in the lowlands of Lesotho have developed in cultivated areas, it is doubtful whether overgrazing has had a significant impact on gully erosion. Although the custom of letting the livestock graze the maize and sorghum stalks left in the cultivated fields during winter, or remove the stubble to be used for fuel, may have increased the potential for erosion. Indirectly, overgrazing on the colluvial slopes below the escarpments may have increased the runoff reaching the fields below, but it rather seems as if unsuitable cultivation practices and conservation measures, and a lack of maintenance of the latter, have had a greater and more direct impact on gully erosion. It may well be that the original transition from grassland to cultivation immediately induced and increased gully erosion. Starting in limited areas, it then increased in severity and extent as cultivation expanded due to more efficient farming methods and population increase. Bad management,

little use of fertilizers and deterioration of the nutrient status of the soils then served as the entrance to a vicious circle of decline. The ultimate result is reduced yields and, consequently, less cover and increased erosion, leading to further nutrient loss.

It appears as if human activities tend to more directly influence the development of discontinuous gullies, e.g. along terraces or cattle tracks, than the initiation of new headcuts along the walls of existing gullies. The latter seems to be more part of the natural gully erosion process, even though human impact may originally have initiated the main gully. The discontinuous gullies then fuse and join the major gullies through gully erosion processes. The development of tributary gullies along the gully walls may, however, be accelerated through human activities, indirectly, for example, by cultivation and tree planting that leads to infiltration and piping, and directly through paths and roads entering the gullies. In other words, once initiated, through human activities or natural causes, the gully erosion process will continue, but perhaps at a higher rate due to human impact. If discontinuous gullies are largely initiated as a result of human activities, the high and increasing percentage and number of discontinuous gullies in Mafeteng 1 may reflect a lower management level in that catchment compared to the less eroded Maseru 1.

5.3 Final remarks

It cannot be said that one factor, e.g. rainfall, is the sole cause of the accelerated gully erosion in Lesotho, the factors are interrelated. A decrease in rainfall will lead to a deterioration in the vegetation cover, but vegetation is also affected by grazing. Tree planting and conservation measures may reduce the overland flow, but increase the throughflow and deep piping. The rainfall factor in the study catchments may exemplify this complexity. The catchments were chosen in pairs with similar rainfall conditions. Gully development in the two catchments within each pair has been entirely different, except for the two Leribe catchments, e.g. Maseru 2 being the most severely eroded and at the end of an erosion cycle, while Maseru 1 is the least eroded of the eight catchments and in the beginning of a cycle. The thresholds have been reached at different times in the catchments but it is not exclusively due to the factor of rainfall.

Williams (1981, p. 155) stated that:

"... those terrain characteristics important in initiating gullying are often different from those leading to its further extension: for example, once initiated, a gully system may readily extend into areas with a vegetation cover much too dense to have permitted initiation there."

The statement is certainly valid in Lesotho and applies to morphology, soils, vegetation and human activities alike. It also applies to rainfall where, for example, a heavy downpour may initiate a gully which then extends in conjunction with less erosive rains that otherwise would not have been able to initiate the gully.

There are varying opinions as to what extent human activities have influenced gully erosion in different regions in Africa. Stocking (1981) claims that human impact is very low and that random fluctuations in variables such as degree of piping, catchment size, height of headcut, and amount of rainfall to a large extent explain the growth and extent of gullies in central Africa. Egboka and Nwankwor (1985, p. 417-418), working in a region in Nigeria with soil conditions and gully processes similar to those in the Lesotho lowlands, found that:

"While deforestation and other human activities might have contributed to the development of the gully complex, it is believed its origin and growth are chiefly influenced by the hydrogeological and geotechnical characteristics of the area. The human factor is believed to be of secondary significance."

Whitlow (1988), on the contrary, claims that population density and land tenure have had a great influence on sheet and gully erosion in Zimbabwe.

In Lesotho, human impact on gully erosion appears to have been relatively large, indirectly through the high and increasing population density, and more directly e.g. through gully initiating conservation measures and cultivation practices. The population density in the mid-1800s was low and the people spread out along both sides of the Caledon River, into the now bordering Orange Free State of the Republic of South Africa. In 1868, Lesotho (then

Basutoland) was declared a British protectorate and in the treaty, all the fertile lowlands west of the Caledon River were lost to the Orange Free State (Parsons, 1982; Min. of Agric., 1986b). The people were pushed back to the east of the Caledon River and had to spread into the foothills and mountains. The territory was limited and the increasing demand for agricultural land led to cultivation of marginal lands and land fragmentation, and the continuous cropping led to depletion of soil nutrients.

The soils of Lesotho are, even in their undisturbed natural state, extremely vulnerable to gully erosion, both through surface runoff and piping. They have not been able to withstand the rough treatment they have been receiving during this century and the later part of the 1800s. Sheet and gully erosion are also found in the neighbouring Orange Free State in the west, but they are less severe than in Lesotho. The soils and the climate in the eastern part of the O.F.S. are similar to the lowlands of Lesotho, but several differences in extrinsic factors have given rise to the difference in erosion. The population density has long been much lower in the O.F.S. In 1946, the figure was 7 inhabitants/km² compared to 18 in Lesotho, and in 1980, 15 compared to 44 (Dep. of Agric. Econ. & Market., 1987; Bur. of Statistics, 1988). This is the population density for the whole of Lesotho. In the lowland districts it is much higher, 33 and 81 respectively in the Mafeteng District for example. Already in the mid-1800s the farms in the O.F.S. exceeded 1 000 ha in size and were privately owned due to farm standardization by the British Government (Christopher, 1982). This should be compared to the average area of an allocated farm holding in Lesotho of 2.4 ha in 1950 (Morojele, 1963a) and about 1 ha in 1986 (Bur. of Statistics, 1987b). The large farms in the O.F.S. reduce the influence of land fragmentation as a contributing factor to gully erosion. It can also be assumed that the incentive to maintain the conservation measures and good cultivation practices, and to use fertilizers to maintain the soil's nutrient status is larger for farmers who own their land privately. Consequently, maize yields, for example, are on average three times greater in O.F.S. than in Lesotho (Dep. of Agric. Econ. & Market., 1987; Bur. of Statistics, 1985).

Scherer (1978, p. 14) stated that:

"On the slopes up to 8 %, just farming on the contour reduces the soil loss by half. On the steeper slopes the reduction is less but it is substantial. This illustrates the tremendous benefits Lesotho has received from the contour bunds and grass strips that were installed in the 1930s, 40s and 50s."

This is a slight exaggeration, and Beinart (1984, p. 64) speculates that:

"It could indeed be argued that it was the disastrous attempts of the colonial government in Lesotho to introduce compulsory anti-erosion measures, with little advance research but merely visits to the USA and South Africa, that produced more widespread dongas (gullies)."

Conservation initiatives taken in Lesotho, e.g. grass strips, terraces and tree plantations, have not been effective, rather the opposite. The soils of the lowlands of Lesotho are very prone to piping and the increased infiltration and deeply penetrating tree roots in combination with the conservation measures and tree planting along the gullies favoured piping, and probably increased rather than hampered gully erosion in the process. Furthermore, gully erosion through surface runoff along terraces, in depressions in the cultivated fields, along field borders and cattle tracks, have contributed to the presently very dense network of gullies in the lowlands.

Baillie et al. (1986, p. 31), working in Tunisia, noted that:

"Contour banking, even if well-constructed and intact, appears to be ineffective against piping, and may actually exacerbate the problem."

"The vulnerability of contour banking to piping, and the latter's tendency to initiate a train of erosion events has been known in Australia for many years. Soil conservationists there, counsel against the construction of unnecessary terraces and banks on soils that are susceptible to piping."

"A typical management sequence in a slightly piped area might well begin with deep ripping and cross ripping to break up existing pipes."

Cross-ripping of piped areas may also work in Lesotho, at least in the case of the shallow type of piping. The problem of piping at 5-6 m below the soil surface is an entirely different matter. The deep penetrating roots of the poplars planted along some of the gullies in the catchments of Leribe 1 and 2, and Maseru 1, and which favour infiltration, probably accelerated and increased the gully development through deep piping in these catchments.

Conservation measures in Lesotho to prevent or delay further gully development have to be balanced to avoid too much infiltration and percolation, and too much runoff. As the deep kind of piping depends on existing gullies, i.e. an exposed gully wall, the best protection against it would be to keep a wide zone beside the gully under permanent, dense and healthy grass cover, instead of planting trees along the gullies. This would also offer protection against the development of tributary gullies through surface runoff. The dense grass cover uses the water effectively, a factor that will reduce percolation of the infiltrating water to piping prone horizons deeper down in the profile and, furthermore, the grass does not have thick and deep penetrating roots. In addition, the grass cover will dampen the effects of wetting and drying that may otherwise give rise to potential piping sites in the form of cracks and fissures in the top soil layer. The desirable width of the grass zone is difficult to state, but the thought of keeping 100-200 m on both sides of a gully under permanent grass cover, instead of using it for cultivation, is daunting to the farmers and does not agree with the acute land shortage in the lowlands. Strip cropping and cover cropping may be alternatives. Agroforestry, on the other hand, should be avoided, at least on soils prone to piping.

If landuse is not adjusted to the suitability of an area, the result is almost unavoidably land degradation. This has been noted by several authors, e.g. Dudal (1981). It is certainly true in Lesotho and applies to conservation measures as well as cultivation practices. They have to be adjusted to the local conditions such as soils that may be truly local (Fig. 5.5). The natural vegetation in Lesotho is grassland and the question arises whether trees should be planted in an environment that does not naturally support trees. Other aspects such as provision of fuel wood and building materials complicate the matter, but tree planting in the wrong location in Lesotho may prove more destructive than useful.

Once initiated, gully extension and expansion are hard to prevent. A gully that extends is to some extent self-suppressing, since the area it drains will decrease when the head migrates upslope. Less water is collected at the head and extension is slowed down. Simultaneously, however, new gullies develop along the gully walls, and the main gully is widened. Check dams across the gully is one possible measure to prevent further development. If not properly constructed, and in particular if the soil is prone to piping, these efforts are usually fruitless, however. The check dams are often built without a spillway in the centre and hence the runoff may attack the gully walls. Piping and seepage may also act on the sides of the check dam. Several examples of failures can be seen in the study catchments, e.g. Mafeteng 2 and Mhales Hoek 1. Dressing the gully walls with rocks is also a relatively common method to prevent gullying, but it is also inefficient in piping- and seepage-prone soils. Discontinuous gullies, when not initiated through piping, appear to be easier to stop than, for example, a tributary, which extends from a main gully. The former will not give rise to tributaries if measures are taken before the gully has developed too far. In Leribe 1 some of the small discontinuous gullies have been successfully stabilized by the construction of check dams.



Figure 5.5. Cultivation of marginal lands in Mohales Hoek 1. An area 10 by 20 m surrounded by gullies in a piping-prone zone is being cultivated (April 1, 1988).

6 CONCLUSIONS

The aim of the present study was: 1. to determine the present state of gully erosion in the selected study catchments and identify the ones most severely eroded; 2. to determine the effects on gully erosion of different intrinsic and extrinsic variables; and 3. to analyse and explain the differences in gully extent and erosion rates observed between the catchments. The results of the study can be summarized as follows:

The state of gully erosion in the catchments

The studied eight catchments show different gully development over the period under study, and may be ranked in descending order of severity of gully erosion: Maseru 2 > Mohales Hoek 1 > Leribe 2 > Leribe 1 > Mafeteng 1 > Mafeteng 2 > Mohales Hoek 2 > Maseru 1. Maseru 2 and Mohales Hoek 1 were severely eroded already in 1950.

The catchments have individual gully erosion cycles and Maseru 2 is considered to be at the end of a cycle while Maseru 1 is at the beginning. The study shows that several parameters have to be considered when determining the state of gully erosion in a catchment. Drainage density or gully area alone do not suffice. Erosion rates, gully head development, slope above headcut etc. have to be taken into account.

Two types of piping were found in the catchments. A shallow type that develops in the B-horizon, and a deep type that develops deeper down in the parent material, where conditions are favourable. The former type dominates in Leribe 1 and 2, and Maseru 1, and the latter in Mafeteng 1 and Mohales Hoek 1. The deep type is dependent on an exposed gully wall to develop, while the shallow type may develop anywhere on a slope where conditions allow. The piping index used gives a minimum measure of the extent of piping in the catchments. Piping is most prominent in Mafeteng 1.

Impact of intrinsic and extrinsic variables

Slope angle does not have a direct impact on gully erosion. Gullies are found on very low slopes. A steep average slope above the gully heads in a catchment should be seen as a sign that the gullies have extended and the heads have reached closer to the escarpment or water divide, rather than being a factor that affects the extent and rates of gully erosion. The slope angle may contribute indirectly, however, since it affects the distribution of soils and material available for gully erosion through both surface and subsurface runoff.

The local bedrock topography may affect gully erosion by limiting the fusion of discontinuous gullies. The bedrock surface may also act as an impermeable layer and induce piping in shallow soils. Where the depth of soil and parent material is limited and the bedrock surface is exposed in the gully bottom gully widening is a prominent process. This is reflected in the higher correlation between gully length and gully depth than gully area and gully depth in the grid square analyses.

The factor of antecedent rainfall conditions is important. The rainfall analyses showed that in search of potentially erosive rainfall sequels, an analysis of annual records alone is far from satisfactory. The annual rainfall may be normal, but large deviations within the year may have occurred and an analysis at least on a monthly basis is necessary. The results of the inventory of the monthly records revealed several potentially erosive dry-wet sequels during the period under study. However, when comparing the results with the erosion development in the catchments no definite conclusions can be drawn. The catchments were selected in pairs with similar climatic conditions. Despite this, gully development in all cases is entirely different between the two catchments within each pair, except for the two Leribe catchments. It can be concluded that the difference in erosion in the catchments cannot be ascribed to rainfall alone.

The analysis of rainfall trends since 1921 at the four meteorological stations showed that the trend is steeply negative in Leribe. Although only one station in the northern lowlands was analysed and the record is relatively short, the result is alarming in that it indicates that the climate in that area is getting drier at a rapid rate. The matter merits further study.

The correlation between gully length or area and the distribution of duplex soils is relatively low and it is clear that gully erosion is in no way confined to soils of a duplex nature.

There is also a low correlation between piping and duplex soils, a fact which indicates that these soils are not a prerequisite for piping to occur. This is particularly the case with the deep kind of piping.

The effects on gully erosion of a change in baselevel are very local in character. The positive effects of a reservoir can only be noticed a limited distance upstream and deposition only occurs in the gully mouths in the immediate vicinity of the dam. In the gully network, however, a lowering of the baselevel may locally accelerate and reinitiate gully erosion, e.g. where pipe roofs collapse and tributary gullies have to adjust to the new level.

Some of the main gullies in the catchments of Leribe 1 and 2, and Maseru 1 and 2, have trees and bushes growing on the debris in the main gullies, which apparently has a stabilizing effect. Erosion may still be active in the upper reaches of the gullies, however. The trees and bushes planted on top of the gully walls in Leribe 1 and 2, and Maseru 1 rather promotes than prevents further gully development. The deep kind of piping is prominent in these catchments and the deep, penetrating roots favour infiltration and pipe initiation. The planting of trees as a conservatory measure in the lowlands is therefore dubious, especially in piping-prone soils. Agroforestry should be avoided. A dense and healthy grass cover is more protective. The infiltration will be high (runoff low) but the water used efficiently. The dense vegetation also reduces the desiccation cracking.

Gully erosion has been evident in Lesotho at least since the middle of the last century. The present distribution of gullies in the lowlands is not only the result of recent events and conditions. The increase in population has led to land fragmentation, cultivation of marginal lands, exhaustion of the soils etc., and a general land degradation, all factors increasing the potential for erosion. All of the flatter parts of the lowlands of Lesotho are used for cultivation. This is also where most of the gullies are found. Hence, the extent and severity of gully erosion is more influenced by cultivation and conservation methods than by overgrazing. Locally, however, stock trampling and grazing on terraces and fallow fields, and in the fields after the harvest of maize and sorghum, may increase the potential for gully erosion. The variation in livestock population appears to be out of phase with the rainfall variations, i.e. a peak in the number of livestock may fall during or after a period of drought and the opposite. The variation in livestock is influenced by imports and exports and not related to natural causes alone, but nevertheless a peak when vegetation is sparse during droughts will accentuate the problem of overgrazing.

The use of terraces and grass strips for soil conservation in Lesotho is very doubtful. The soils of the lowlands are highly erodible, and subject to surface and subsurface runoff. The increased infiltration in connection with terraces and grass strips may lead to subsurface seepage and eventually piping. The terrace edge may collapse and a gully headcut be initiated. Gullies also frequently develop along the terraces through surface runoff. Plough furrows in cultivated fields may have a similar effect, since they do not always exactly follow the slope contour and a slight depression immediately collects the runoff, creating a rill and eventually a gully.

Reasons for the difference in gully development

The results of this study and a comparison with other studies of gully erosion in Lesotho indicate that the erosion cycles are highly local and that the thresholds of initiation are crossed at different times in different areas in the same region.

Due to the intricate pattern of intrinsic and extrinsic variables it is extremely difficult to explain the differences in gully extent and erosion rates between the study catchments. The study has further pointed to the complexity of the gully erosion problem in Lesotho and how the process is affected by different intrinsic and extrinsic variables. The results indicate that one factor alone does not cause the crossing of the threshold of a new gully erosion cycle in an area, rather the sum of several stress factors that the area suddenly cannot cope with. The various factors may have different amplitudes and cycles, and when they coincide, the system is brought out of its equilibrium. One factor on its own would not have had severe effects but the joint effort of several factors pushed the system across the threshold. The system may thus be balancing on the edge of failure and, at a critical stage, one final factor joining the others, may trigger the collapse and the initiation of an erosion cycle. One example is a main gully that through the combined efforts of several variables is extending upslope in a catchment. As the gully extends, erosion in the gully and along the walls is relatively slow. When the gully head reaches a zone with soils and parent material vulnerable to deep piping,

a spell of rapid extension and expansion and initiation of tributary gullies will start. The piping, in turn, may have occurred due to soil conditions, tree roots and infiltrating water.

A certain amount of gully erosion is natural, but the human activities have not been in harmony with what the environment can cope with. The intrinsic variables in Lesotho have together rendered the system very susceptible to disturbances. The impact of extrinsic variables (e.g. landuse) in accelerating the process has been considerable. Conservation methods, cultivation practices, and other factors extrinsic to the system have not been adapted to the intrinsic conditions, with subsequent land degradation and accelerated erosion as the result.

APPENDIX 1: SOIL PROPERTIES AND DESCRIPTIONS

This appendix contains:

1. Table 21 showing the scientific names of the soil series present in the studied areas, according to the US Soil Taxonomy and FAO system.
2. Brief general descriptions of the different soil series and units present in the areas.
3. Table 22 summarizing some useful facts about the soil series.

Table 21. Soil classifications.

Lesotho soil series (type profile)	US Soil Taxonomy (1) Order Suborder	FAO classification (2)
Caledon	Entisols	Typic Udifluvents
Majara	"-	"-
Ntsi	"-	Lithic Udorthents
Berea	Inceptisols	Aquic Dystrochrepts
Matele	"-	Dystic Eutrochrepts
Sephula	Alfisols	Albaquic Hapludalfs
Maseru	"-	Typic Albaqualfs
Tsiki	"-	"-
Leribe	"-	Ultic Paleustalfs
Ralebese	Mollisols	Typic/Lithic Hapludolls
Maliele	"-	Cumulic Hapludolls
Bela	"-	Typic Argiaquolls
Maseru dark	"-	Cumulic Haplaquolls
		Eutric/Calcaric Fluvisols
		Solodic Planosols
		Lithosols
		Plintic Acrisols (?)
		Ferric Luvisols
		Solodic Planosols
		"-
		"-
		Ferric Luvisols
		Haplic Phaeozems
		Haplic Luvisols
		Mollic Gleysols
		Gleysols (?)

(1) From Schmitz and Rooyani (1987), who modified the classifications made by Conservation Division (1979a) and Cauley (1986). The classification has been revised several times since Cons. Div. published "Soils of Lesotho" in 1979 (a). This is the most recent classification, but not necessarily the final one.

(2) From Anonymous, 1984.

General description of the soil series and units present in the study catchments

This section has been compiled from Conservation Division (1979a; 1979b) and from Schmitz and Rooyani (1987).

Caledon (Ca)

This is a well drained, deep and coarse texture soil. The topsoil is dark brown to yellowish brown and loamy sand to sandy loam, underlain by lighter coloured and coarser textured alluvium. It is formed in alluvial deposits along Lesotho's major rivers and is well stratified as to colour, texture and organic matter content. It is used for cropping but has limitations due to its coarse texture and low fertility.

Majara (Mj)

This is a moderately well drained deep, coarse texture soil. The upper layer of the soil is a dark brown to yellowish brown loamy sand. This stratified layer is underlain by dark clay and buried duplex soil (Tsiki, Maseru or Sephula). This is the major characteristic of the Majara soil. The parent material is alluvial and colluvial, sandy and loamy materials weathered from

sandstone. The soil occupies drainage ways and interfluvies on level to gentle slopes below sandstone scarps. The major limitation to cropping is the clay accumulation zone that causes to a difference in hydraulic conductivity and severe erosion hazard.

Ntsi (Nt)

This is a well drained, shallow, coarse to medium texture soil. The greyish to yellowish brown ochric topsoil is underlain by a lithic contact, sandstone, within 50 cm of the surface. The soil is formed in loamy or sandy residuum or colluvium on the crest or sides of sandstone outcrops (Clarens Formation) in the lowlands and foothills. Due to the limited depth, and often steep slope, it is unsuitable for cropping.

Berea (Ba/Bb)

This is a moderately well to somewhat poorly drained deep soil. The topsoil is an acidic, yellowish brown to dark yellowish brown fine sandy loam to loam. The upper layer is underlain by a yellowish brown to dark yellowish brown loam to clayloam, acidic and mottled subsoil. The parent material is loamy residuum mainly derived from sandstone (Clarens Formation). These soils occupy gentle to moderately steep slopes in the lowlands and foothills. They are suitable for cropping, provided that some of the limitations due to poor natural fertility and acidity are corrected.

Matela (Md)

This is a well to moderately well drained deep soil. The topsoil is dark, acidic reddish brown, sandyloam to loam, overlying a yellowish red, sandyloam to clayloam acidic subsoil. Distinct mottles of dark reddish brown and soft phillite nodules are present in the lower part of the solum. The parent material is coarse loamy residuum from sandstone and basalt. The soil occupies gentle slopes in the contact zone between sandstone and basalt in the foothills, and between dolerite and sandstone in the lowlands. Limitations to cropping are low fertility and strong acidity.

Sephula (Se)

This is a somewhat poorly to poorly drained, duplex soil. The topsoil is a (dark greyish) brown sandyloam or loam, underlain by a pale brown, sandyloam or loam albic horizon. The upper layer rests on a brown to yellowish brown, mottled, gravelly sandy clayloam to clay argillic horizon. The gravels are mostly in the form of ironstone nodules. This soil is formed in two-storied, strongly-contrasting material. The lower clay-textured material is derived from weathered sandstone residuum or a weathered mixture of sandstone and shale or basalt. The soil occupies undulating to gently rolling and mostly concave slopes in the northern and central lowlands. It has severe limitations of erosion and impeded drainage and is best suited to pasture.

Maseru (Me)

This is a poorly drained, moderately deep to deep, duplex soil. The topsoil consists of a dark greyish brown loam and clayloam ochric surface horizon, and a greyish or light brownish grey loamy rather thick albic horizon. The upper layer rests abruptly on a grey, mottled clay argillic horizon. The soil is usually found in mid-valley position on transportation sediments derived from shale and sandstone. Maseru soils have severe limitations of erosion and impeded drainage that restrict their use and limit the range of suitable crops.

Tsiki (Ts)

This is a poorly drained, moderately deep, duplex soil. The ochric surface epipedon consists of a dark greyish brown, fine sandyloam layer, and a greyish brown (sandy) loam albic horizon. The upper layer rests on a greyish brown, gravelly sandy clayloam argillic horizon. The solum is underlain by residuum of fine grained sandstone and aeolian silt. Tsiki soils occupy nearly level to gently sloping areas in the lowlands and foothills. The soil has severe limitations of erosion and impeded drainage and is best suited for permanent pasture. The main difference between this soil and other duplex soils is that the Tsiki soil has a lower level of clay in its argillic horizon.

Leribe (Le)

This is a well drained, deep, medium texture soil. The topsoil is a dark reddish brown loam to fine sandyloam. The subsoil is a dark reddish brown or dark red (sandy) clayloam to silty clay. The solum rests on a buried relict reddish clayloam to clay argillic horizon. The lower portion of the soil may have dark mottles or aggregates of iron and manganese. These soils are formed, in part, from fine loamy residuum derived from sandstone or a mixture of sandstone and basalt sediments, and, in part, from overburden aeolian sediments. Leribe soils are mainly found in sandstone controlled terrain, in the northern and central lowlands and foothills. It can be used for intensive cropping if the fertility status is improved.

Ralebese (Ra)

This is a well drained, shallow to moderately deep, and medium texture soil. The surface layer is a dark reddish brown and gravelly loam which rests on a paralithic basalt/dolerite saprolite. The soil occupies moderately steep slopes of dolerite dykes in the lowlands, the foothills and the mountains. It may be as shallow as 20 cm. This is a major limitation for cropping and the soil is best suited for improved pasture.

Maliele (Mg)

This is a well to moderately well drained, very deep, medium texture soil. It has a topsoil of dark brown to black, sandyloam to clayloam, which rests on a dark brown (sandy) clayloam subsoil. The soil has formed on sandstone derived colluvium and occupies gentle slopes in the foothills. The soil, when found on gentle slopes, has no major limitations for intensive cropping.

Bela (Be)

This is a poorly drained, deep, and medium texture soil. The topsoil is a very dark greyish brown loamysand to clayloam which rests on a black to very dark brown clayloam to clay buried alluvial soil. The parent material is basaltic alluvium derived from the mountains and foothills. The soil occupies nearly level to gently sloping areas usually in the middle of broad alluvial valleys, on slopes or in depressions between hills or gentle land rises. Bela soils are well suited to farming if excess water can be removed.

Maseru dark (Mk)

This is a poorly drained, deep and medium to fine texture soil. It has a black to dark brown and loamy to silty clayloam topsoil overlying a greyish brown (sandy) silty clayloam subsoil. The soil is formed in moderately fine to fine textured alluvial sediments or reworked sedimentary clays that in most sites are overlain by medium to moderately fine texture alluvial and/or aeolian sediments. The soil occupies nearly level areas on alluvial terraces of major streams in the western lowlands. Maseru dark soils are used for cropping, but have limitations of erosion and impeded drainage.

The following four paragraphs have been summarized from Conservation Division (1979b).

Colluvial land (Co)

A land type that occupies strongly sloping to steep, usually plane, convex or slightly concave slopes at the base of sandstone escarpments (Clarens and Elliot Formations) or interlayered sandstone and basalt escarpments. The soil has dropped from sandstone and basalt escarpments and accumulated at the base. The debris is then transported downhill by gravity forces and surface wash. Soil material consists of undifferentiated, variable-sized, angular and sub-angular fragments of basalt and sandstone in a sandy-clayey matrix derived from the weathered product of the two rocks. Large areas of stones, exposed bedrock and very small spots of e.g. Leribe, Matela, Ntsi, Berea, Maliele and Tsiki soils are present. Internal drainage is medium. Geologic and accelerated erosion keep pace with soil formation so that soil profile development is weak.

Rough broken land (RI)

This is a miscellaneous land type that consists of both deep and shallow soils that are poorly developed and occupy steep broken slopes. The soils are badly mixed and are derived from mixed shale and sandstone. Soil textures range from clay to sandy loam in a broken pattern. Vegetation cover is sparse. Surface runoff is rapid and soil erosion extensive.

Rockland sandstone (Rs)

This land type occupies areas marginal to sandstone escarpments. Slopes range from 1-35 %. Small areas of e.g. Ntsi and Berea soils may be present. Internal drainage is rapid to slow. Erosion in most areas removes soil as fast as it forms.

Rockland basalt (Rb)

This landtype occurs mostly in the mountains but also in areas marginal to basalt escarpments or along streams that traverse thinly soil-mantled, basalt bedrock-controlled terrain. The unit occupies uniform plane or convex slopes ranging from 1-35 %. Included in this unit are small areas of Ralebese soil. Internal drainage is medium to slow. Erosion in most areas removes soil as quickly as it forms.

Table 22. Some general properties of the soils in the study areas.

Soil series (map symbol)	Origin of parent material (1)	Texture of surface hor. (2)(3)	Erodibility K-value (4)	class (5)	Tolerance to erosion (2)(5)
Caledon (Ca)	Alluvial dep.	loamy fine sand	0.18	low	n.a.
Majara (Mj)	B,M,E	-"	0.55	high	mod.
Ntsi (Nt)	C	fine sandy loam	0.42	mod.	low
Berea (Ba)	C	loam	0.32	mod.	low
Berea (Bb)	C	loamy fine sand	0.49	mod.	low
Matela (Md)	C	fine sandy loam	0.32	mod.	low
Sephula (Se)	B,M,E	loam	0.39	mod.	low
Maseru (Me)	B,M,E	loam	0.60	high	low
Tsiki (Ts)	B,M,E	fine sandy loam	0.56	high	low
Leribe (Le)	B,M,E	loam	0.28	mod.	low
Ralebese (Ra)	L	loam and stony loam	0.40	mod.	low
Maliele (Mg)	B,M,E	loam	0.22	low	mod.
Bela (Be)	Alluvial dep.	loamy fine sand	0.42	mod.	n.a.
Maseru dark (Mk)	Alluvial dep.	loam	0.46	mod.	low

n.a. = not available

(1) From Berding (1982). Geological formations: Burgersdorp (B), Molteno (M), Elliot (E), Clarens (C) or Lesotho (L).

(2) Scherer, 1978.

(3) Conservation Division, 1979b.

(4) Erodibility index (k-value) introduced by Wischmeier and Smith (1978) in the USLE equation. K-values for Lesotho soils provided by Scherer (1978) and Conservation Division (1979a).

(5) Class limits according to Cauley (1986):

Erodibility (k-value) Tolerance to erosion(ton/ha/year)

Low	< 0.25	< 4
Moderate	0.25-0.50	4-8
High	> 0.50	> 8

Tolerance to erosion expresses the ability of a soil to withstand soil loss without a decrease in productivity over time (ibid.).

Table 22. Continued.

Soil series (map symbol)	Internal drainage (6)	Clay content of control section (%)(7)	Natural fertility (8)	Extent in Lesotho (%)(9)
Caledon (Ca)	mod.good-good	< 10	low	0.06
Majara (Mj)	fairly poor-mod.good	< 18	mod.	0.12
Ntsi (Nt)	well-excess.	< 15	low	3.98
Berea (Ba)	fairly poor-mod.good	18-35	low	3.96
Berea (Bb)	-"-	n.a.	n.a	incl. in Ba
Matela (Md)	mod.good-good	< 18	low	1.97
Sephula (Se)	poor-fairly poor	35-60 arg.	low	1.38
Maseru (Me)	very poor-poor	35-60 arg.	low-mod.	0.67
Tsiki (Ts)	-"-	18-27 arg.	low	0.09
Leribe (Le)	mod.good-good	18-35	low	1.57
Ralebese (Ra)	good	< 27	mod.	2.34
Maliele (Mg)	fairly poor-mod.good	18-35	mod.	0.27
Bela (Be)	very poor-poor	35-60 arg.	n.a.	0.09
Maseru dark (Mk)	-"-	18-35	n.a.	0.14

(6) Berding, 1982.

(7) Control section = between 25 and 100 cm depth, or if an argillic (arg.) horizon is present in the solum, the uppermost 50 cm of that horizon (Berding, 1982).

(8) Berding, 1984b. Classification based on TEB (total exchangeable bases) of the A-horizon:

Low	< 5 meq/100 gram soil
Moderate	5-15
High	> 15

(9) Values from Conservation Division (1979a). All the soils of Lesotho have not been included in this table, hence, the sum is less than 100 %. The value for "Colluvial land" is 1.37 %, for "Rockland sandstone" 7.30 % and for "Rockland basalt" 17.42 %. No value is available for "Rough broken land".

APPENDIX 2: CLASS LIMITS FOR GRID SQUARE INVENTORY

For the grid square inventory of the catchments class limits were determined for some of the parameters (see Table 7). These class limits are described below.

Presence of piping:	Class	1	No piping detected
	2		Piping detected along < 50 % of the gully sides
	3		Piping detected along > 50 % of the gully sides
	0		No gullies are present in the square and therefore no piping detected

Soil erodibility:

This classification combines the k-values (erodibility) given by Scherer (1978) and Conservation Division (1979a)(see Appendix 1) for the different soils present in the grid squares. Where the classification is high the soil in the square is easily erodible, i.e. material is available for gully erosion. The land types "Rockland sandstone", "Rockland basalt" and "Colluvium" have not been given a k-value by Conservation Division and, judging by the degree of gully erosion in these landtypes, erodibility is low. No k-value is available for "Rough broken land" either, but judging by the properties of this landtype and the extent of gully erosion the erodibility is tentatively set to moderate. The classification of soil erodibility in the grid squares was based on the following scheme:

Rockland or colluvium (% of square)	k < 0.25 (% of square)	k 0.25-0.50 (% of square)	k > 0.50 (% of square)	Erodibility class
100	0	0	0	Class 1
> 75	< 25	0	0	1
> 75	0	< 25	0	2
> 75	0	0	< 25	2
50-75	25-50	0	0	2
50-75	0	25-50	0	3
50-75	0	0	25-50	3
25-50	50-75	0	0	2
25-50	0	50-75	0	3
25-50	0	0	50-75	4
< 25	> 75	0	0	2
< 25	0	> 75	0	3
< 25	0	0	> 75	4
0	100	0	0	3
0	> 75	< 25	0	3
0	> 75	0	< 25	3
0	50-75	25-50	0	3
0	50-75	0	25-50	4
0	25-50	50-75	0	3
0	25-50	0	50-75	4
0	< 25	> 75	0	4
0	< 25	0	> 75	4
0	0	100	0	4
0	0	> 75	< 25	4
0	0	50-75	25-50	4
0	0	25-50	50-75	4
0	0	< 25	> 75	5
0	0	0	100	5

Duplex soils:	Class 1	No duplex soil in the square
	2	< 25 % of the square covered with duplex soil
	3	25-50 %
	4	50-75 %
	5	> 75 %

Gully depth:	Class 1	< 3 m
	2	4-10 m
	3	> 10 m

Gully depth was estimated in the field and the accuracy of the estimation is assumed to decrease with increasing gully depth, hence the coarse class division.

Sheet and gully erosion according to the SARCCUS classification system (Anon., 1981):

Class 1	No apparent erosion
2	Slight erosion (noticeable)
3	Moderate erosion (clearly noticeable but less than 25 % of the grid square affected)
4	Severe erosion (25-50 % of the grid square affected)
5	Very severe erosion (more than 50 % of the grid square affected)

Landuse:

This classification is very rough. It is assumed that the runoff potential is highest for settlement areas (Class 5), lower for cultivated areas (3) and lowest for grazed areas (1). Settlement areas have very little or no ground cover. The distinction between the two other types of landuse is based on the SLEMSA manual (Anon., 1976) where the average protective cover of low yielding maize is considered to be less than for pasture in a poor condition. The cover ratings may very well vary significantly from region to region, and during the season, depending on crop type, yield, degree of overgrazing etc. This was noticed by Chakela (1987) when conducting an erosion hazard survey of Lesotho. Intermediate classes (2,4) were assigned to grid squares where more than one type of landuse was found.

APPENDIX 3: STATISTICAL FORMULAE

The following section is compiled from McClave and Dietrich (1982).

The Spearman ranking correlation coefficient is a measure of the correlation between rankings of two different variables. The values of each variable are ranked from high to low. The rankings are then compared and the correlation coefficient calculated as:

$$r_s = 1 - \left(\frac{6 \sum_{i=1}^N d_i^2}{N^3 - N} \right)$$

where N= number of samples and d= difference in ranking between the two variables

The significance of the result can be determined by comparing the t-value:

$$t = r_s \sqrt{\frac{(N - 2)}{1 - r_s^2}}$$

with the Student's t-distribution where N-2 represents degrees of freedom. When $t \geq t_{\alpha}$ the correlation is statistically significant.

APPENDIX 4: MAPS AND AIR PHOTOS USED

A list of the maps and air photos covering the different study areas is presented below. The numbers and letters refer to official Lesotho indexes. The 1983 colour photos were not used in this study but are included in the list.

Leribe 1

Topographical maps:	2828 CC (1:50 000)
	2828 CC 3 (1:20 000)
Geological map:	2828 CC (1:50 000)
Air photos 1950:	82/E/101 5231-5233
1961:	57/BS/9 22-24
1980:	179/LE/24 4, 7, 10
1983:	30 10-12

Leribe 2

Topographical maps:	2828 CC (1:50 000)
	2828 CC 3 (1:20 000)
Geological map:	2828 CC (1:50 000)
Air photos 1950:	82/E/101 5229-5231, 5476-5477
1961:	57/BS/10 56-58
1980:	179/LE/25 182, 185, 188
1983:	31 13-15

Maseru 1

Topographical maps:	2927 BC (1:50 000)
	2927 BC 1, 2927 BC 2 (1:20 000)
Geological map:	2927 BC (1:50 000)
Air photos 1950:	82/E/125 5464-5466
1961:	57/BS/2 30-31, 153-154
1980:	179/LE/46 40, 43, 46
1983:	18 11-13

Maseru 2

Topographical maps:	2927 BC (1:50 000)
	2927 BC 1, 2927 BC 2 (1:20 000)
Geological map:	2927 BC (1:50 000)
Air photos 1950:	82/E/125 5466-5468
1961:	57/BS/2 31-33
1980:	179/LE/44 45, 48, 51
1983:	18 9-10

Mafeteng 1

Topographical maps:	2927 CA, 2927 CB (1:50 000)
	2927 CA 4, 2927 CB 3 (1:20 000)
Geological maps:	2927 CA, 2927 CB (1:50 000)
Air photos 1950:	82/E/98 5164-5165
1961:	57/BS/2 9-10
1979:	179/LE/16 187, 191
1983:	08 10-12

Mafeteng 2:

Topographical maps:	2927 CB (1:50 000)
	2927 CB 3, 2927 CB 4 (1:20 000)
Geological map:	2927 CB (1:50 000)
Air photos 1950:	82/E/119 5073-5075
1961:	57/BS/10 17-19
1979:	179/LE/16 207, 211, 215
1983:	12 20-22, 11 15-16

Mohales Hoek 1:

Topographical maps:

3027 AB (1:50 000)
 30 27 AB 2 (1:20 000)
 3027 AB (1:50 000)
 82/E/100 5440-5444
 57/BS/6 63-65
 179/LE/35 34, 37, 40
 12 41-43

Geological map:

Air photos 1950:
 1961:
 1980:
 1983:

Mohales Hoek 2:

Topographical maps:

3027 AB (1:50 000)
 3027 AB 4 (1:20 000)
 3027 AB (1:50 000)
 82/E/102 5156-5158
 82/E/101 5106-5109
 57/BS/22 31-33
 179/LE/6 81, 84, 87
 13 58-60

Geological map:

Air photos 1950:
 1962:
 1979:
 1983:

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